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INVESTIGATION OF PLANE STRAIN SHEAR TESTING. REPORT 1. WES HIGH-CAPACITY PLANE STRAIN SHEAR APPARATUS

Mosaid M. Al-Hussaini

Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

March 1971

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Report 1

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13. ABSTRACT

The stress-strain conditions in many practical problems, such as retaining walls, embankments, and bearing capacity problems, can be approximated by plane strain conditions. In order to gain fundamental understanding of the behavior of soil or to analyze and predict the stresses within such structures, laboratory tests should be conducted under conditions similar to those existing in the field, i.e., plane strain conditions. Thus there is a need for plane strain apparatus that can simulate field conditions; this need formulates the basis of this study. The immediate concern of this study was to review and evaluate plane strain apparatus used by previous investigators and to design and construct a plane strain apparatus that incorporated outstanding features of previous apparatus. The new plane strain apparatus tests soil specimens 16 in. long, 5 in. high, and 2 in. wide under plane strain conditions with complete ability to apply and measure principal stresses. It also enables measurement and control of strains in the directions of principal stresses. With this apparatus the specimen can be consolidated under isotropic or anisotropic stress conditions and can be sheared under drained or undrained conditions with measurement of pore water pressure. Two series of tests on crushed Napa basalt were conducted in the new plane strain apparatus. In the first series, the initial relative density of the specimen was 70 percent, while in the second series, the initial relative density was 100 percent. Each series consisted of two tests: the specimen of the first test was consolidated under K_o condition; the specimen of the second test was consolidated isotropically; and both were sheared under drained conditions at a confining pressure of 60 psi. Calibration and demonstration testing indicate the WES high-capacity plane strain shear apparatus to be precise, flexible, and efficient in operation. It is believed to represent a significant addition to the capability of the U. S. Army Corps of Engineers for testing soils under conditions more closely simulating in situ conditions.

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ARMY-MRC VICKSBURG, MISS

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FOREWORD

In July 1966, the Office, Chief of Engineers (OCE), authorized the U. S. Army Engineer Waterways Experiment Station (WES) to develop equipment and techniques for performing plane strain tests and to investigate the stress-deformation characteristics of soils under plane strain conditions. The work was supported by Engineering Study (ES) 538, entitled "Investigation of Plane Strain." Reviews of available information on plane strain testing were made intermittently during the period from July 1966 through November 1967 by Messrs. B. N. MacIver, W. T. Robbins III, and J. L. McRae, and Dr. M. M. Al-Hussaini of WES. In November 1967, criteria for the design of a plane strain apparatus were approved by OCE, and funds were provided by OCE and from the WES plant program for its fabrication.

The WES high-capacity plane strain apparatus was designed by Dr. Al-Hussaini, Laboratory Research Section, Embankment and Foundation Branch, Soils Division, and the shop drawings were prepared by Mr. G. J. Stevens, Engineering Branch, Construction Services Division. The components were fabricated by Messrs. J. L. Hill and J. M. Regan, Machine Shop, Shops Branch, Construction Services Division. Assistance in instrumentation and calibration was provided by Mr. T. V. McEwen, Measurements and Testing Section, Instrumentation Branch, Technical Services Division. Soil test specimens were prepared and tested by Dr. Al-Hussaini and Mr. F.G.A. Hess, and Mr. L. Devay assisted in reduction and presentation of data; these individuals are members of the Laboratory Research Section.

This report was prepared by Dr. Al-Hussaini under the general supervision of Mr. B. N. MacIver, Chief, Laboratory Research Section, and Mr. J. R. Compton, Chief, Embankment and Foundation Branch. Messrs. W. J. Turnbull (retired) and J. P. Sale were Chiefs, Soils Division, and Mr. A. A. Maxwell (deceased) was Assistant Chief, Soils Division, during the period of the investigation. This report was reviewed by Mr. S. J. Johnson, Special Assistant, Soils Division.

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COL John R. Oswalt, Jr., CE; COL Levi A. Brown, CE; and COL Ernest D. Peixotto, CE, were Directors of WES during the investigation and preparation of this report. Mr. F. R. Brown and Mr. J. B. Tiffany were Technical Directors.

CONTENTS

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
square inches	6.4516	square centimeters
pounds	0.45359237	kilograms
tons (2000 lb)	907.185	kilograms
pounds per square inch	0.070307	kilograms per square centimeter
Fahrenheit degrees	5/9	Celsius or Kelvin degrees*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) reauings, use: $K = (5/9)(F - 32) + 273.15$.

SUMMARY

The stress-strain conditions in many practical problems, such as retaining walls, embankments, and bearing capacity problems, can be approximated by plane strain conditions. In order to gain fundamental understanding of the behavior of soil or to analyze and predict the stresses within such structures, laboratory tests should be conducted under conditions similar to those existing in the field, i.e., plane strain conditions. Thus there is a need for plane strain apparatus that can simulate field conditions; this need formulates the basis of this study.

The immediate concern of this study was to review and evaluate plane strain apparatus used by previous investigators and to design and construct a plane strain apparatus that incorporated outstanding features of previous apparatus. The new plane strain apparatus tests soil specimens 16 in. long, 5 in. high, and 2 in. wide under plane strain conditions with complete ability to apply and measure principal stresses. It also enables measurement and control of strains in the directions of principal stresses. With this apparatus the specimen can be consolidated under isotropic or anisotropic stress conditions and can be sheared under drained or undrained conditions with measurement of pore water pressure.

Two series of tests on crushed Napa basalt were conducted in the new plane strain apparatus. In the first series, the initial relative density of the specimen was 70 percent, while in the second series, the initial relative density was 100 percent. Each series consisted of two tests: the specimen of the first test was consolidated under K_o condition; the specimen of the second test was consolidated isotropically; and both were sheared under drained conditions at a confining pressure of 60 psi.

Calibration and demonstration testing indicate the WES high-capacity plane strain shear apparatus to be precise, flexible, and efficient in operation. It is believed to represent a significant addition to the capability of the U. S. Army Corps of Engineers for testing soils under conditions more closely simulating in situ conditions.

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INVESTIGATION OF PLANE STRAIN SHEAR TESTING

WES HIGH-CAPACITY PLANE STRAIN SHEAR APPARATUS

PART I: INTRODUCTION

1. In most design and research testing, engineers use conventional triaxial compression apparatus to obtain the strength design data. In conventional triaxial compression tests, stresses applied to a soil specimen and the resulting strains are axially symmetrical. However, such stresses and strains are comparable to few real situations in the field.

2. Many practical problems in soil mechanics can be approximated by plane strain conditions in which the maximum deformations occur mainly in two orthogonal directions. Loading conditions characterized by plane strain deformation occur in both natural and compacted soil masses and structures, such as embankments, retaining walls, dams, long footings, etc. However, plane strain conditions may not always occur, even in long embankments, because of varying subsoil profiles or variation in physical properties. Nevertheless, plane strain behavior of embankments and foundations is of much practical interest.

3. At present, design methods for plane strain problems commonly utilize the shearing resistance values determined by conventional triaxial tests. This subjects the soil specimen in the laboratory to stress conditions that are quite different from those existing in the field. As a result, design data obtained from laboratory tests may either underestimate or overestimate (depending on the stress condition) the true value of the strength parameters. Thus there is need for evaluating and possibly improving current testing techniques by introducing more realistic testing procedures and developing testing equipment to better approximate actual field conditions.

States of Stress in Laboratory Testing and Their Practical Implications

4. The state of stress that can be imposed on a soil specimen is dependent upon the testing equipment and testing procedure adopted by the investigator. While an infinite number of stress systems may be generated in the laboratory, from the practical viewpoint, the laboratory investigator should impose on the soil specimen a stress state either identical to that existing in the field or one corresponding to the most critical stress condition expectable during the life of the structure. In many cases the difficulties and cost involved in duplicating field conditions in the laboratory result in use of routine testing devices or procedures that may impose stress conditions far different from those existing in the field. The stress states that can be created in the laboratory can be put in two categories: axial symmetry and plane strain.

Axial symmetry

5. The geometry of a solid cylindrical specimen makes it ideal for imposing axially symmetric states of stress or states of strain. On the other hand, the solid cylindrical specimen is limited to two axially symmetric states of stress: axial compression and axial extension. Assume that 1, 2, 3 are the coordinates of the principal axes; σ_1 , σ_2 , σ_3 are the principal stresses; ϵ_1 , ϵ_2 , ϵ_3 are the normal strains in the direction of the principal stresses; and γ_{12} , γ_{13} , γ_{23} are the shear strains acting in the principal planes. Further assume that σ_r is the radial stress and σ_a is the axial stress and that a state of uniform stress exists within the cylindrical specimen. Under the axial compression, shown in fig. 1a, the axial stress is equal to the major principal stress and the radial stress is equal to the intermediate and minor principal stresses, i.e., $\sigma_a = \sigma_1$ and $\sigma_r = \sigma_2 = \sigma_3$ and $\sigma_1 > \sigma_2 = \sigma_3$. This case, for example, simulates the stress condition at any point beneath the center of a circular loaded area, as beneath a storage tank. Under the axial extension, shown in fig. 1b, the radial stress is equal to the major and intermediate principal stresses and the axial stress is equal

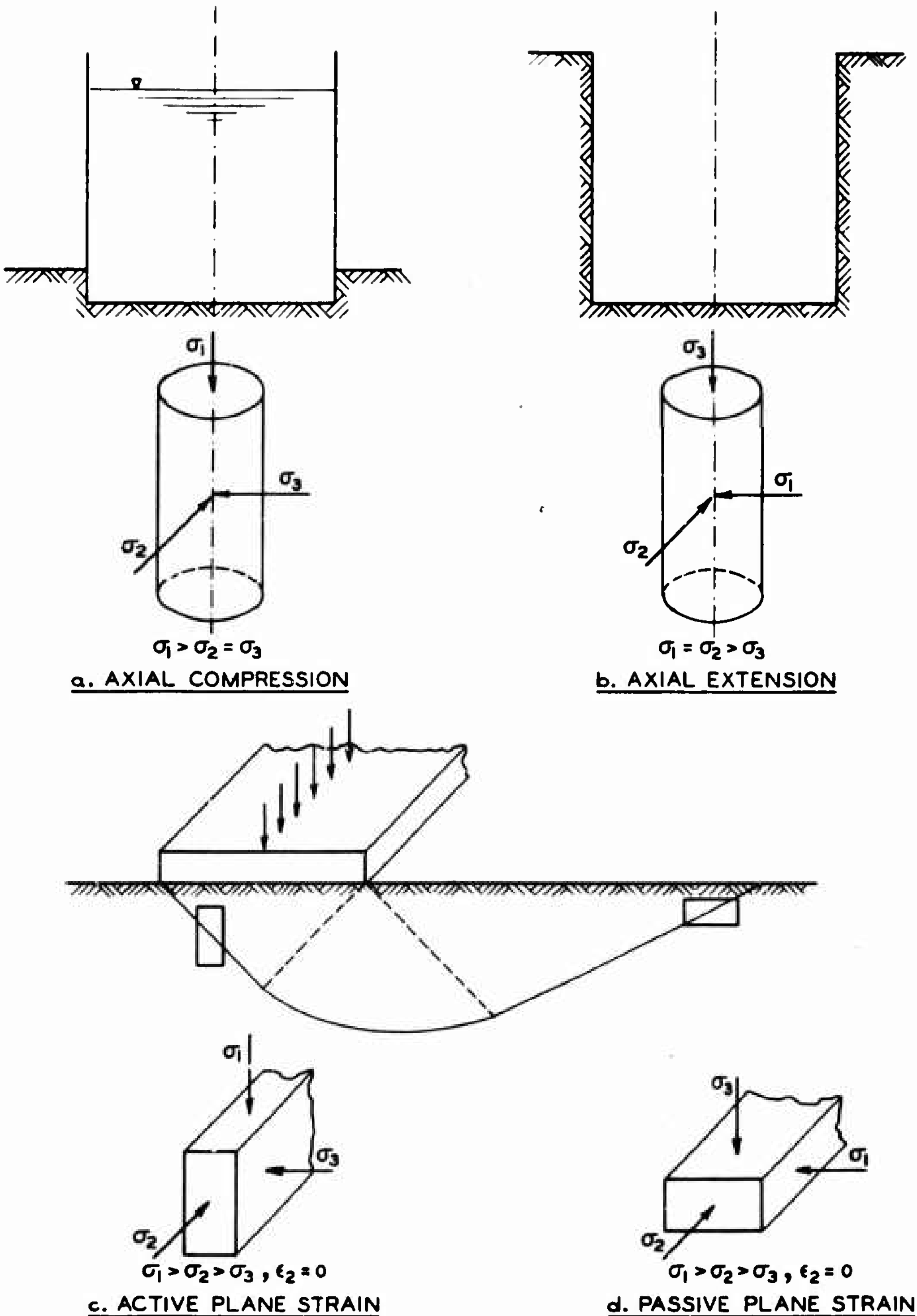

Fig. 1. Examples of typical states of stress in the field

to the minor principal stress, i.e., $\sigma_r = \sigma_1 = \sigma_2$, $\sigma_a = \sigma_3$, and $\sigma_1 = \sigma_2 > \sigma_3$. In axial compression and axial extension, radial strains exist; however, if yielding is prevented in the radial direction, each element of soil will exhibit strains only in the vertical direction. Such a state of stress is referred to as one-dimensional consolidation, or K_o condition. This case simulates the stress condition associated with settlement of homogeneous soil under a large level area uniformly loaded. It also resembles the stress condition behind a long smooth rigid retaining structure with uniformly distributed vertical stress on the surface of the soil behind the structure.

Plane strain

6. Plane strain is always characterized by two-dimensional deformation. Under plane strain, the soil element is subject to three principal stresses, $\sigma_1 > \sigma_2 > \sigma_3$, so that deformations associated with principal stresses take place only in the intermediate principal plane. Thus plane strain conditions exist only if $\epsilon_2 = \gamma_{12} = \gamma_{13} = 0$. However, since principal stresses are being dealt with, then γ_{12} , γ_{13} , and γ_{23} must be equal to zero. The state of stress that satisfies plane strain conditions may exist in most of a long earth structure provided that the loading condition on any plane perpendicular to the length is the same. However, local differential settlement may change a normal plane strain condition to one in which σ_2 approaches σ_3 .

7. There are two limiting stress states that satisfy plane strain conditions: active and passive plane strain states. In the active plane strain state, as shown in fig. 1c, the major principal stress acts in the vertical direction while the minor principal stress acts in the horizontal direction. In the passive plane strain state (fig. 1d), the horizontal stress, which in this case is equal to the major principal stress, is larger than the vertical stress, which is equal to the minor principal stress. Thus, it is obvious that the major and minor principal stresses rotate during the transition from the active to the passive plane strain conditions. The intermediate principal stress, on the other hand, in both active and passive cases remains perpendicular to the plane containing the

major and minor principal stresses. Some plane strain situations in the field can be classified as either active or passive; however, there are situations, as shown in fig. 1, where both cases can exist.

8. To summarize, the majority of practical problems in applied soil mechanics can be simplified to either axial symmetry or plane strain conditions. The state of stress associated with each case is different, and the soil strength parameters under each stress system are expected to be different. Therefore, laboratory testing will be appropriate only when soil specimens are tested under conditions approximating those existing in the field.

Purpose of the Study

9. The purpose of this phase of the work was to initiate a study leading to development of a plane strain apparatus that could be used to test cohesionless and other materials under various placement densities and ranges of confining pressure and to evaluate the performance of such a device with regard to stresses, strains, volume changes, and other variables that determine the deformation characteristics of the soil under plane strain conditions.

Principle of Plane Strain Testing

10. The basic principle of plane strain testing is to subject the soil specimen to three principal stresses acting perpendicular to its boundaries, preventing any strain in the intermediate principal stress direction. To meet these objectives two things have to be fulfilled. First, shear stresses on the boundaries should be eliminated. Second, the axes of principal stresses and principal strains should be the same. This means that there is no choice but to assume that the material is homogeneous and isotropic; otherwise, plane strain conditions cannot be met.

11. The testing concept adopted for this study is shown in fig. 2, and in its simplest form consists of a prismatic soil specimen that is subjected to three independent stresses: the major principal stress σ_1, the intermediate principal stress σ_2, and the minor principal stress σ_3. By keeping the length of the specimen constant during the application of stress, it can be assumed that the strain along the intermediate principal stress at any point is equal to zero.*

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* This assumption needs to be verified by strain measurement at different locations within the soil specimen to determine the extent of its validity, but no attempt has yet been made to do this.

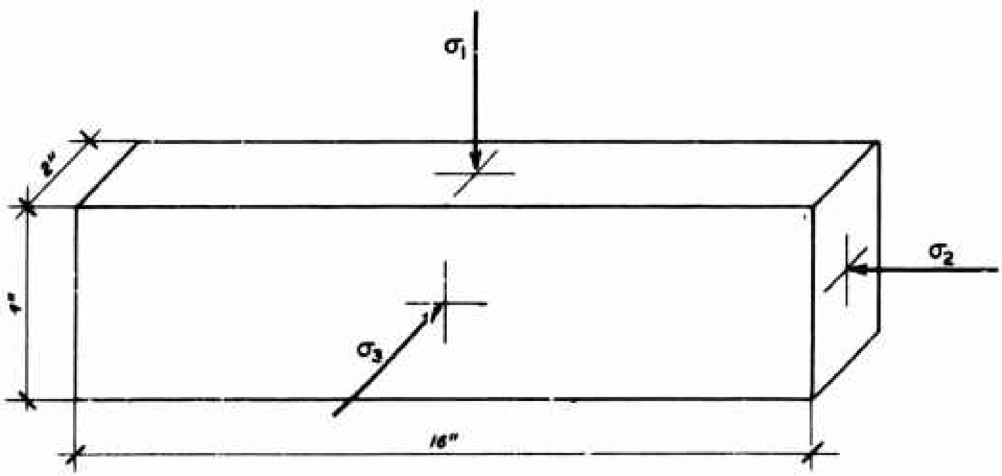


Fig. 2. Representation of principal stresses acting on the soil specimen

PART II: APPARATUS DEVELOPED BY OTHERS

12. The problem of accurate representation of the strength of soil has become increasingly important in recent years. Special efforts have been made in the last three decades to define more precisely the strength of soil under various stress systems. In order to achieve this objective, a wide variety of testing techniques and testing equipment has emerged from the conventional triaxial apparatus, which is limited to two states of stress: axial compression and axial extension. A number of these developments are described and discussed in the following paragraphs. However, the present discussion is limited to the features of the various apparatus; results obtained using these apparatus will be reviewed and compared in subsequent reports of test results produced under ES 538. Table 1 summarizes specimen dimensions and maximum chamber pressures of the various plane strain shear devices.

Kjellman Triaxial Apparatus

13. Among the early apparatus which could produce three independent principal stresses is the one developed by Kjellman.[1] The apparatus, shown schematically in fig. 3, consists of a 62-mm cubical specimen encased inside a rubber membrane and subjected to pressure on its boundaries by means of small rods. One hundred rods on each side were used; each rod was 6 by 6 by 32 mm, with one end resting on the rubber membrane while the other end was forced against a steel plate. The amount of stress applied on each side of the specimen was computed from the total force applied to the rods divided by the area on which they were acting. The deformations within the soil specimen were calculated from the relative movement of each steel plate from its original position; these deformations were limited by the gaps between the adjacent rods. The apparatus was not widely used simply because of the difficulties involved in preparing the specimen. Similar apparatus have been described by Lorenz, et al.[2] in which a plane strain state of stress was created.

Table 1

Summary of Plane Strain Shear Devices

Ref No.	Designer or Sponsor	Location of Equipment	Dimensions of Specimen width x height x length	Max Chamber Pressure Used
1	Kjellman	Technical University of Stockholm	6 x 6 x 6 cm	6 kg/sq cm
2	Lorenz et al.	Technische Universitat, Berlin	10 x 10 x 10 cm	3.5 kg/sq cm
3	Bjerrum and Kummencje	Norwegian Geotechnical Institute	4 x 12 x 30 cm 4 x 12 x 60 cm	0.8 kg/sq cm
4	Christensen	Danish Geotechnical Institute	100 x 50 x 100 cm	Unknown
5	Leussink and Wittke	Technical University of Karlsruhe	20 x 60 x 100 cm	0.5 kg/sq cm
8	Marsal et al.	Comisión Federal de Electricidad, Mexico	70 x 180 x 75 cm	15.3 kg/sq cm
10	Duncan and Seed	University of California	1.1 x 2.78 x 2.78 in.	--
11	Bishop and Wood	Imperial College, London	2 x 4 x 16 in.	40 psi
14	Dickey, Ladd, and Rixner	Massachusetts Institute of Technology (MIT)	1.4 x 3.5 x 3.5 in.	2.15 kg/sq cm
17	Al-Hussaini and Wade	Georgia Institute of Technology	2 x 4 x 16 in.	285 psi

Note: Throughout this report, units of measure are shown as given by the designer or sponsor. A table of factors for conversion of British units to metric units is presented on page ix.

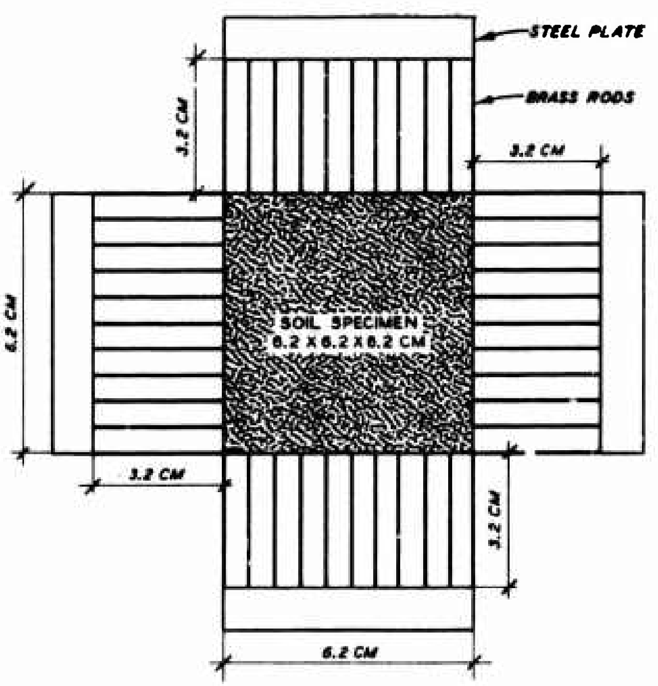


Fig. 3. Triaxial apparatus of Kjellman

Norwegian Geotechnical Institute Apparatus

14. For the past 10 or so years, several attempts have been made to develop plane strain in the United States and other parts of the world. In 1961 a plane strain apparatus was designed at the Norwegian Geotechnical Institute by Bjerrum and Kummencje.[3] The apparatus, as shown in fig. 4, utilized a prismatic specimen (4 cm wide by 12 cm high, having a length ranging between 30 to 60 cm) placed inside a rubber membrane and confined at the top and bottom by stiff plates. In this apparatus no attempt was made to control the length during the test; it was simply assumed that the high ratio of length to width was sufficient to create plane strain conditions. The test procedure consisted of subjecting the specimen to vacuum and subsequently bringing it to failure by gradual increase of axial load. It is believed that the intermediate principal stress was variable and the apparatus could be considered as a conventional triaxial apparatus modified for testing prismatic specimens that may represent a combination of both plane strain and axially symmetric stress conditions.

Danish Geotechnical Institute Apparatus

15. At the Danish Geotechnical Institute, Christensen[4] conducted a series of tests on sand to evaluate the coefficient of active earth pressure under plane strain conditions. The apparatus used in the test program is shown in fig. 5. It consisted of a wooden box, 0.5 m high, with a square base, 1.0 by 1.0 m. The upper half of one of the sides was provided with hinges so that it could rotate about a horizontal axis parallel to the wall and at a distance from it. The rotating wall was divided into three parts and only the central part, which is assumed to be free from the influence of wall friction, was used in measurement of forces and displacements. Several proving rings instrumented with strain gages were placed in contact with the rotating wall to measure the normal and tangential forces exerted by the sand on the rotating

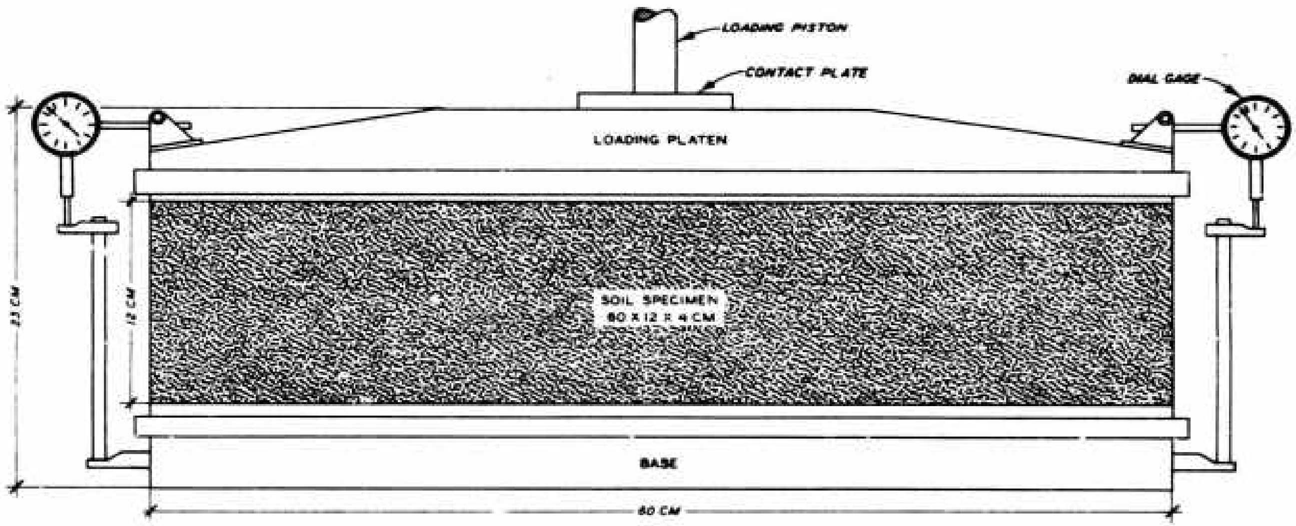


Fig. 4. Norwegian Geotechnical Institute plane strain apparatus

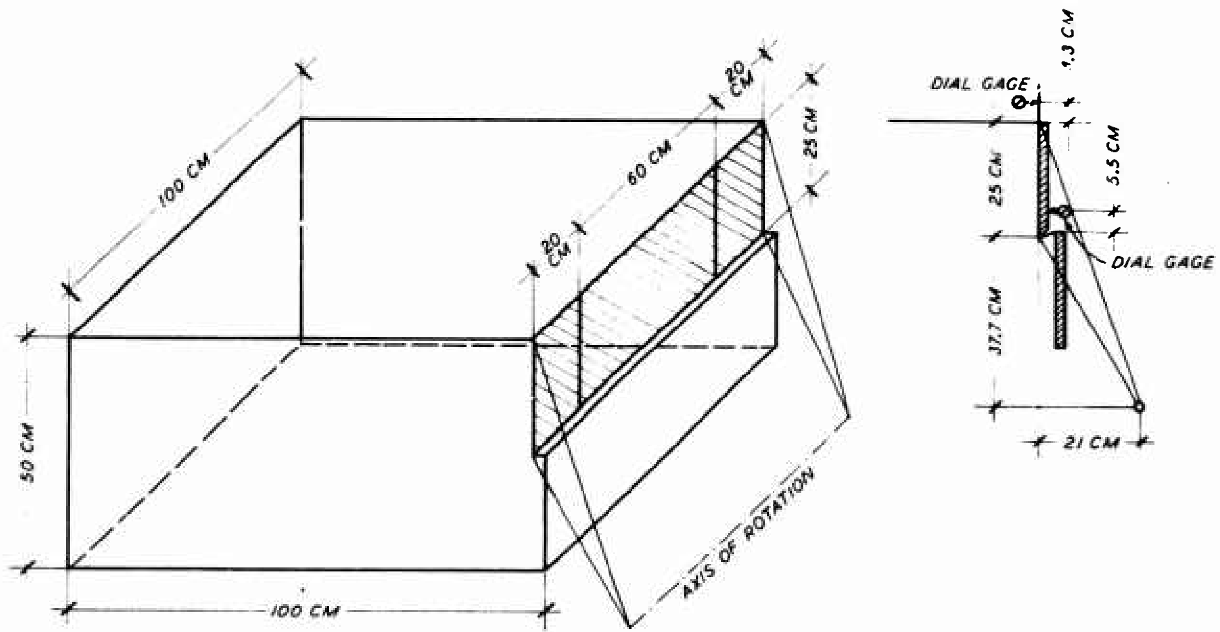


Fig. 5. Plane active earth pressure apparatus

wall during the test. The test procedure used was to fill the box with sand and then rotate the wall slowly until failure occurred. Plane strain conditions were considered to exist in this test only because the width of the material behind the rotating wall was not changed. While this is not typical laboratory apparatus for strength measurements, it was used for measurements of strength under plane strain conditions.

Technical University of Karlsruhe Apparatus

16. Leussink and Wittke[5] of the Technical University of Karlsruhe, Germany, designed a plane strain apparatus that was essentially an improved version of the one designed by Bjerrum. The apparatus, as shown in fig. 6, was used to test prismatic specimens 100 cm long, 20 cm wide, and 60 cm high. The arrangement for applying the intermediate principal stress consisted of two steel boxes filled with water and placed on each end of the specimen. The side of each box in contact with the specimen was a flexible aluminum plate; any tendency for longitudinal deformation of the specimen during the test was detected by movement of water from the two boxes. The steel boxes were provided with pressure gages for measuring the stress in the longitudinal direction of the specimen. The axial load was applied to the specimen by a hydraulic press and measured by a dynamometer; vacuum was used to provide the necessary confining pressure. The test procedure consisted of applying vacuum to the specimen and then increasing the axial load until failure; during the test, the water pressure in the boxes was adjusted so that no movement of the aluminum plates could take place. The apparatus was designed mainly to test regularly composed packings of steel or glass balls of uniform diameters; the porosity and coefficient of friction at the points of contact could be changed. However, its use was limited to very low confining pressure.

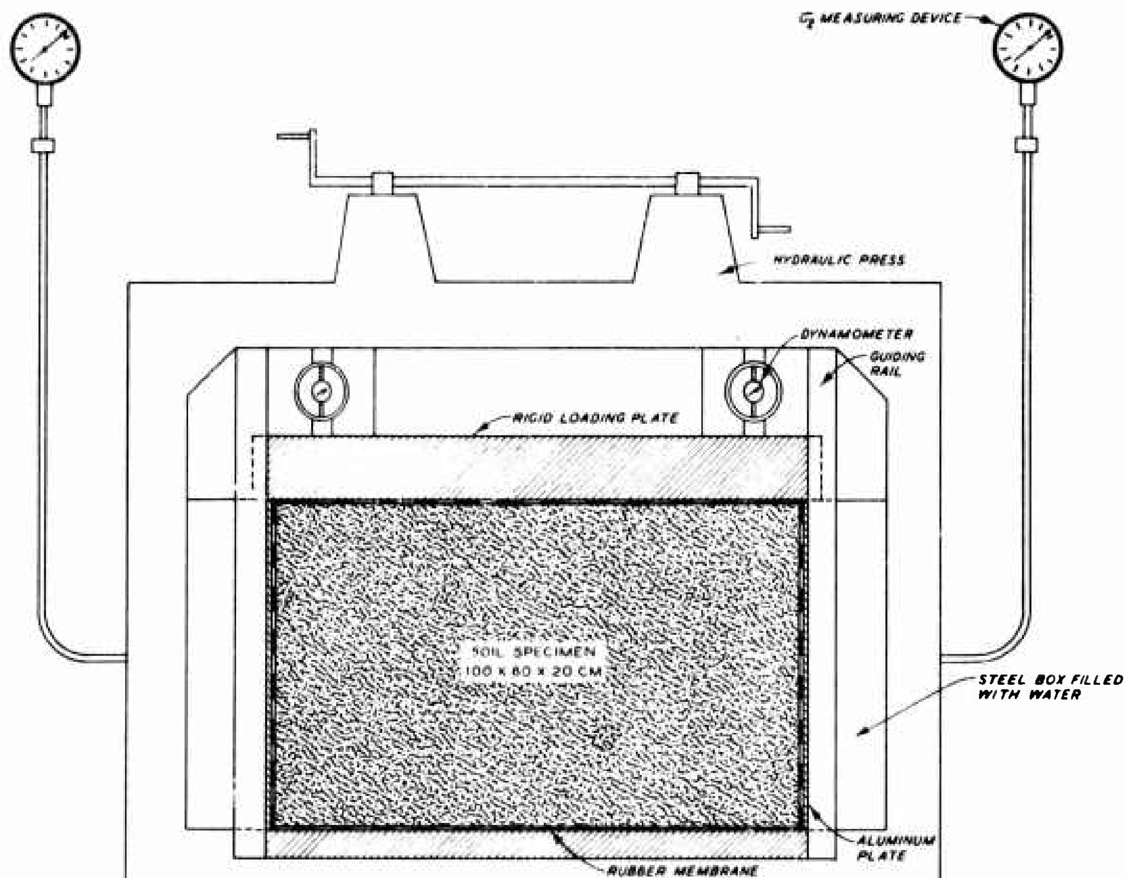


Fig. 6. Plane strain apparatus of Technical University of Karlsruhe

Comisión Federal de Electricidad of Mexico Apparatus

17. The largest plane strain apparatus ever reported was the one designed by Marsal[6] and built at the Comisión Federal de Electricidad to test a 75 by 75 by 180 cm specimen of compacted rock. The apparatus consisted of a steel base and two parallel confining walls, each wall made of ten box girders and connected to the other wall by 20 hollow bars. Elongations of the bars during a test were measured with linear variable differential transformers to permit computation of the intermediate principal stress. The specimen was placed inside a 1/4-in.-thick rubber membrane and separated from the confining walls by several layers of lubricated polyethylene to reduce side friction. Vacuum was used to provide the specimen with the necessary confining pressure; thus the use of the apparatus was limited to low stress levels. The design was later improved by Marsal and his associates[7] by placing the apparatus in a spherical pressure chamber, 4.2 m inside diameter and 1.0 in. thick. The pressure chamber consisted of two hemispheres joined together by 64 bolts to form a spherical shell that enabled the application of confining pressures up to 25 kg per sq cm. However, when the actual plane strain testing began, they found that the rubber membrane was too weak to withstand puncturing, even with the protection of polyethylene layers. Thus the apparatus was redesigned after a few tests and replaced by another plane strain apparatus in which the rubber membrane was eliminated.

18. The new plane strain apparatus was also built by the Comisión Federal de Electricidad in Mexico under the direction of Marsal.[8] The size of the specimen and the two fixed confining walls were kept similar to those used in the first and second apparatus. The major modifications, shown in fig. 7, consisted of two guided walls movable in the direction of the intermediate principal stress and a new arrangement for the base and cap of the specimen. The whole apparatus was surrounded by two loading frames, 2.20 m wide and 4.00 m high, placed 0.95 m apart. The movable walls were made of steel plates, 5.1 cm thick and 195 by 75 cm, hanging on pairs of 24-cm wheels mounted on roller bearings fixed

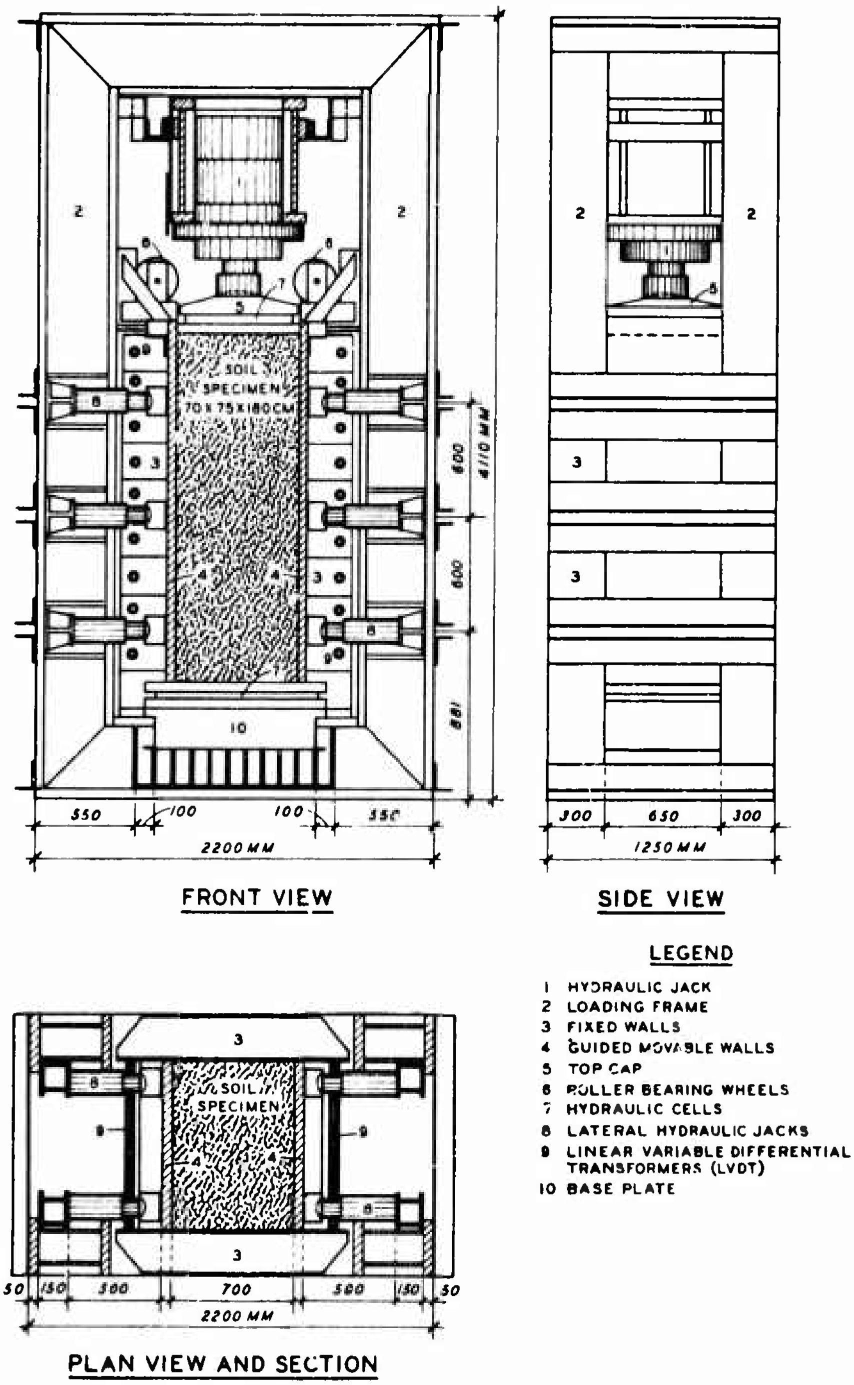


Fig. 7. Plane strain apparatus of the Comisión Federal de Electricidad

to the loading frame. The horizontal force needed to produce the necessary minor principal stress to the specimen was supplied by two sets of six hydraulic jacks, which were mounted eccentrically with their bases fixed to the loading frame and their spherical rams butted against the movable walls. The specimen rested on a steel base, 75 cm wide and 100 cm long, which was supported by five box-type beams; the base plate and the beams were separated by four flat hydraulic cells used to measure the axial load at the base of the specimen. The axial load was supplied by a 600-ton hydraulic jack with its base fixed to the top of the loading frame and its head resting on a truncated-pyramidal cast steel plate. Another structural steel plate, 5 cm thick, 70 cm wide, and 75 cm long, rested directly on the soil and was used to distribute the axial load throughout the specimen. The amount of axial load applied to the soil specimen was measured by four flat hydraulic cells placed between the case and the structural steel plates. The friction forces along the boundaries of the specimen were reduced by covering the interior of the apparatus with three layers of 1-mm-thick polyethylene plates coated on both surfaces with grease. Each plate was a square, 10 cm on the side. Plates in each layer were adequately spaced in order to prevent them from overlapping each other during deformation. The average value of the coefficient of friction recorded by this technique was between 0.03 and 0.05. This was obtained by measuring the difference in the axial force at the top and bottom of the specimen and dividing the results by the lateral area of the specimen times the average value of the minor and intermediate principal stresses. It is more than likely that the stresses on the boundaries and throughout the specimen were not uniform due to the high rigidity of the plates surrounding the soil.

University of California Apparatus

19. A simple plane strain apparatus was designed by Smith[9] at the University of California to test prismatic specimens of soft clay, 3-1/2 in. long, 3-1/2 in. high, and 1-1/2 in. wide. The apparatus consisted of a

Lucite base, which was the foundation of the apparatus, and a Lucite cap through which the axial load was applied to the specimen; both cap and base were provided with porous stones for drainage purposes. Two thick polished plates were placed in contact with the ends of the specimen and tied together by four stainless steel rods so that no longitudinal movement was allowed during shear. The whole assembly could be fitted in a pressure chamber similar to that of the conventional triaxial apparatus. Only one-dimensional consolidation was allowed with the apparatus; however, the value of the confining pressure during consolidation was not known. The apparatus was later modified by Duncan and Seed.[10]

20. The new apparatus, shown in fig. 8, consisted of two polished Lucite plates placed in contact with the ends of the specimen and maintained at a fixed distance by two diaphragm boxes. The dimensions of the specimen that could be tested in this apparatus were 1.1 in. wide, 2.78 in. long, and 2.78 in. high. The apparatus had the advantage of being small and could be fitted inside a triaxial pressure chamber. However, it was not possible to measure either the intermediate principal stress or the value of K_o in this apparatus. The specimen rested on two plates, one made of porous bronze for drainage purposes and the other made of stainless steel; the specimen was also covered by another stainless steel plate. The whole assembly, which included the specimen and the surrounding plates, was placed inside a rubber membrane with its ends pressed between the stainless steel plates on the inside and the Lucite cap and base on the outside, thus isolating the specimen from the confining media. A water-filled rubber diaphragm was placed between the specimen and the diaphragm boxes for applying the confining pressure. When it was required to consolidate the soil specimen under no lateral deformation, the pressure of the water inside the diaphragm was varied continuously during the application of axial load, while the volume of water was kept constant. After several tests, this technique was found to be unsuccessful, since the rubber diaphragms imposed nonuniform lateral deformation along the sides of the soil specimen. This problem was corrected by attaching a stainless steel plate, 1/8 in. thick, to the outside of each rubber diaphragm. At

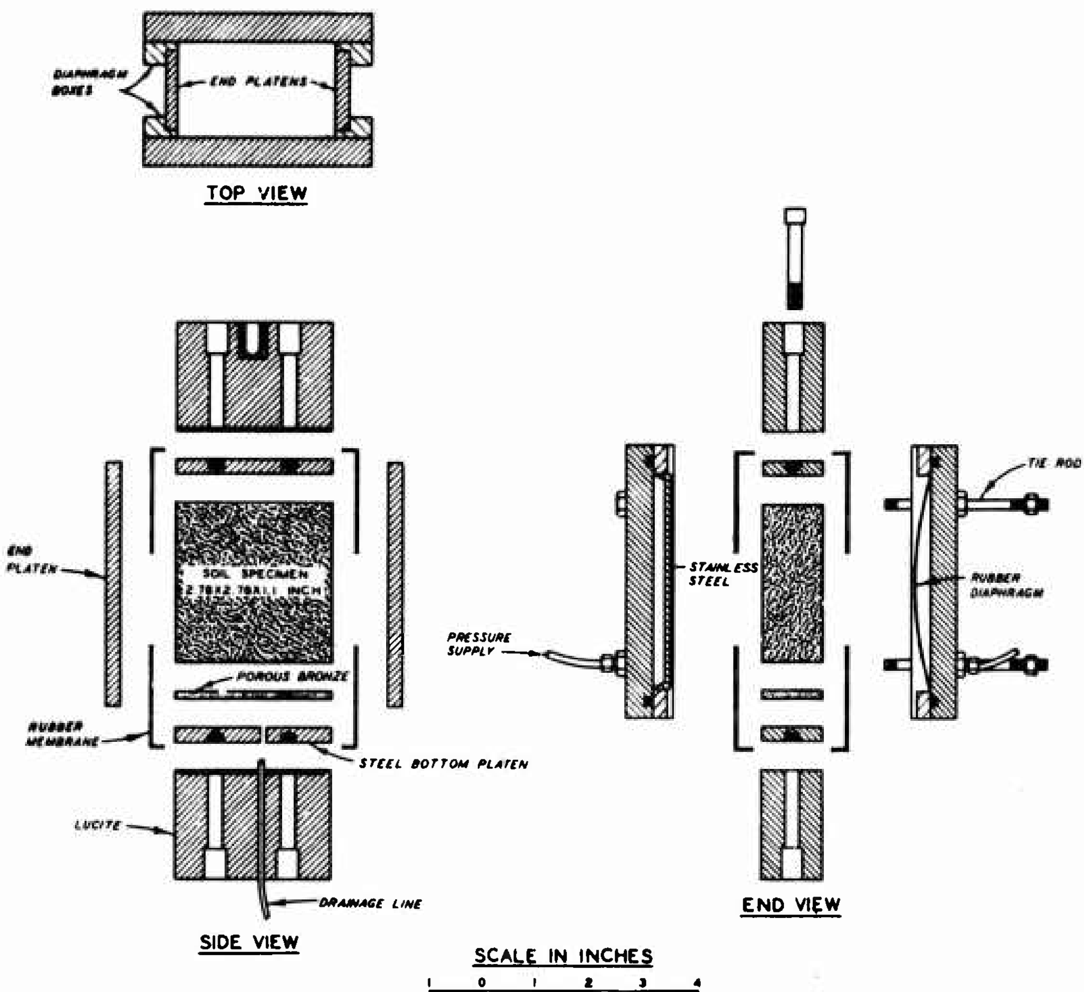


Fig. 8. Berkeley plane strain apparatus; exploded and simplified views

the beginning of consolidation, these plates were pushed against the specimen by increasing the volume of water inside a rubber diaphragm. The plates were maintained in that position during the test.

Imperial College Apparatus

21. At Imperial College, London, another plane strain device was designed by Bishop and Wood,[11] to test a compacted granular morainic material. The apparatus, described by Cornforth,[12] consisted of a rectangular pressure chamber that contained a prismatic soil specimen, 16 in. long, 4 in. high, and 2 in. wide. The specimen was bounded at top and bottom by two brass platens. The lower platen formed the base of the apparatus and was connected to the base of the pressure chamber, while the upper platen was connected to a steel bearing plate. The soil specimen and confining platens were placed inside a rubber membrane. The smaller sides of the specimen were bounded in the longitudinal direction by two aluminum plates. One plate was placed in contact with the specimen, while the other formed the base of a hydraulic cell that was used to measure the intermediate principal stress. The two plates were connected by four rods to keep them firmly in position. The end of the specimen opposite the hydraulic cell was covered by a thin aluminum plate that was connected to the hydraulic cell by a locating pin. The distance between this thin plate and the plate on the other end of the specimen was kept constant during the test; thus the strain in the longitudinal direction was considered to be zero. The hydraulic cell was filled with deaired water and connected by a short lead from the plane strain apparatus to a null indicator filled with mercury. Plane strain conditions were considered to be maintained during the test by continuously keeping the null indicator mercury thread at a constant level (corresponding to no longitudinal deformation of the specimen). The pressure applied to maintain the mercury in the proper position was used in calculating the intermediate principal stress. In this apparatus, no positive approach was used to control the lateral dimension of the

specimen during K_o consolidation.

22. A subsequent modification and additions were introduced to the Imperial College plane strain apparatus. The new additions, described by Wade,[13] consisted of a strain sensor that could indicate any change in length of the specimen and a servo-mechanism connected electrically to the strain sensor to activate the axial load application during consolidation (fig. 9). The advantage of this apparatus is that the three principal stresses can be measured and the axial and longitudinal strains can be controlled. However, it is not possible to control or measure the change in the width of the specimen with this apparatus.

Massachusetts Institute of Technology Apparatus

23. Recently the Massachusetts Institute of Technology (MIT) constructed prototype and production plane strain apparatus. The prototype plane strain apparatus, shown in fig. 10, was designed by Dickey.[14] It was used to test a prismatic specimen of soil, 3.5 in. long, 3.5 in. high, and 1.4 in. wide. The specimen was bounded by upper and lower platens; the upper platen rested directly on the specimen, while the lower platen was separated from the specimen by a porous stone. The soil specimen and the surrounding platens were placed inside a rubber membrane; the upper end of the membrane was sealed between the upper platen and the loading piston; and the lower end was sealed between the lower platen and the base. Two other fixed platens were placed in the front and the back of the specimen. The back platen was connected with the specimen and provided with a small hole to allow the passage of a small pressure transducer, which was used to measure the intermediate principal stress. The front platen was attached to a force transducer, which was also used to measure the intermediate principal stress through a 1-in. by 2-in. plate placed in contact with the specimen. The lateral pressure was applied to the soil specimen by another loading system, called a "right and left horizontal loading system." The right horizontal loading system was similar to that used in the University

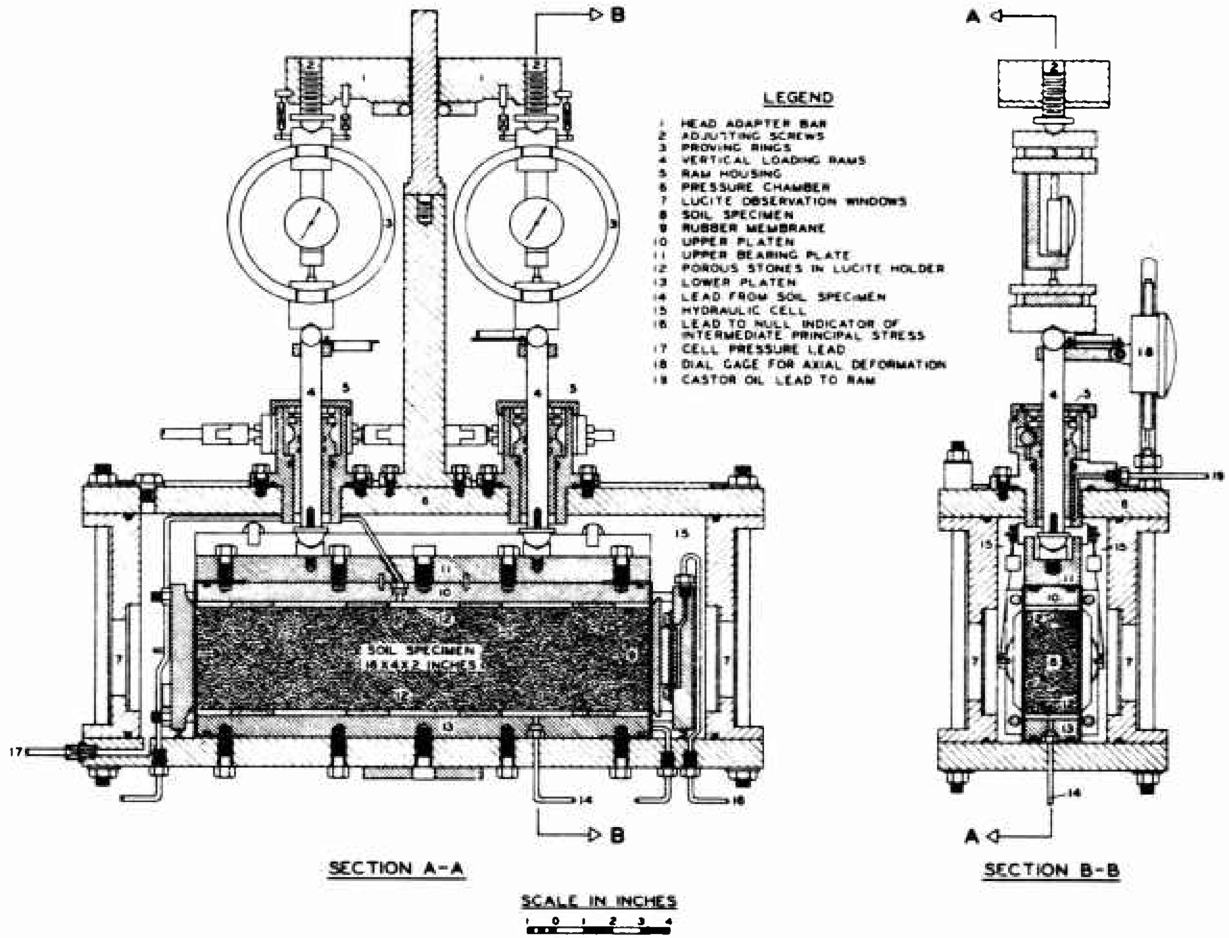


Fig. 9. Imperial College plane strain apparatus

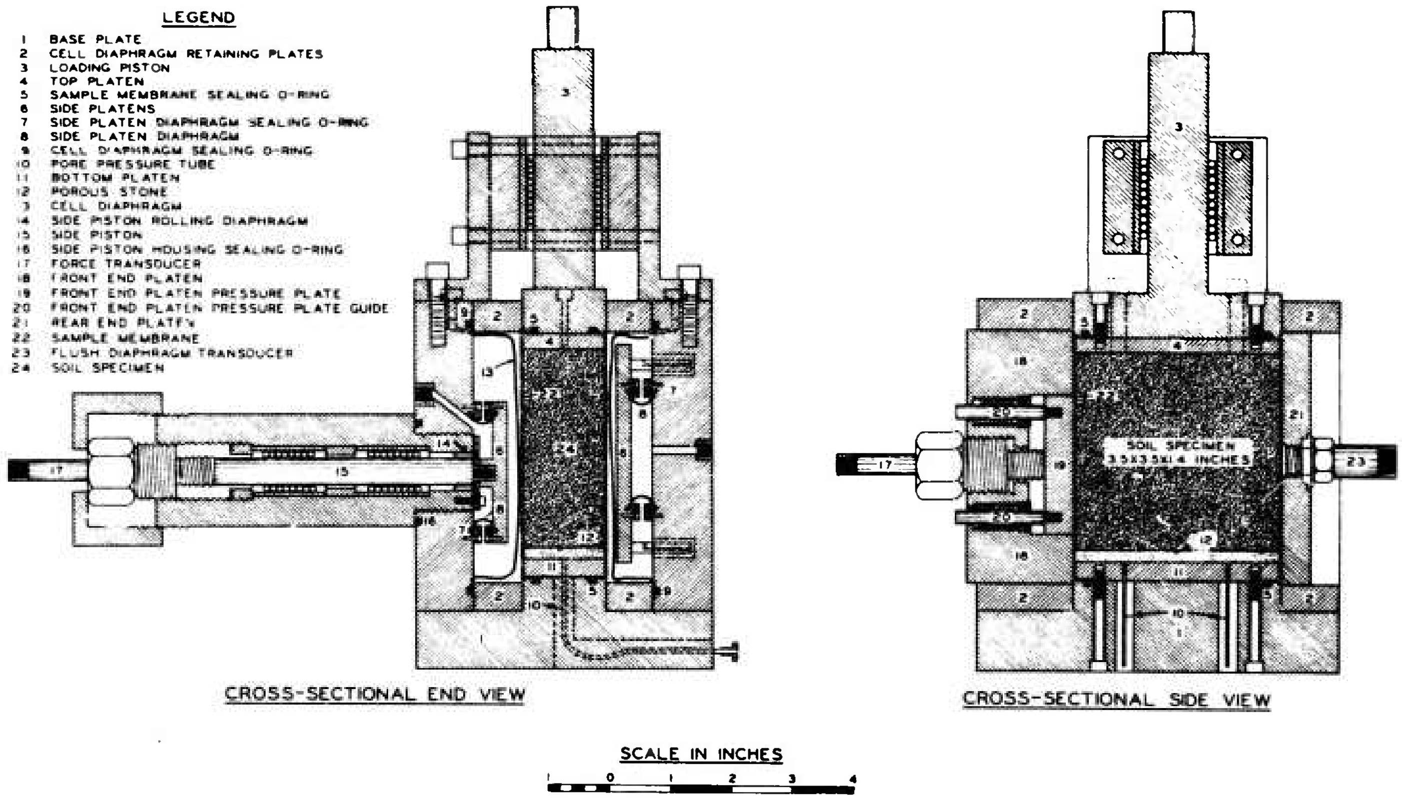


Fig. 10. MIT plane strain device

of California plane strain apparatus. The left loading system consists of a plate that covered most of the central portion of the specimen and a force transducer. The transducer was used either to measure the force required to maintain the side platen in a certain position during K_o consolidation or to measure lateral deformation during shear. The MIT apparatus had the advantage of being small, and stresses and strains could be either measured or controlled on all sides of the specimen. However, this apparatus has some limitations too; for example, the stresses are applied to the specimen through rigid platens that may cause high friction forces as well as nonuniform stress distribution on the boundaries of the specimen.

California Department of Water Resources Apparatus

24. The State of California Department of Water Resources has recently constructed a plane strain apparatus at the Rockfill Testing Facility of the University of California.[15] The apparatus will be used to test specimens (61 cm wide, 137 cm long, and 153 cm high) of large-size granular material under high confining pressure. The specimen will be confined inside a rubber membrane 2.7 cm thick and surrounded at the top and bottom by rigid steel plates. The movement of the specimen in the longitudinal direction will be restricted by two plates held together by four rods. The whole assembly will be placed inside a pressure chamber 4.5 cm thick and 203 cm in internal diameter.

Thick-Walled Cylindrical Specimen Apparatus

25. It is of interest to note that although prismatic shape offers the simplest way of imposing plane strain conditions, other geometrical shapes, such as hollow cylinders, have also been employed. A special plane strain apparatus in which the major and minor principal stresses can be varied independently was developed at MIT by Whitman and Luscher.[16] The apparatus, shown in fig. 11, consisted of a thick-walled cylindrical

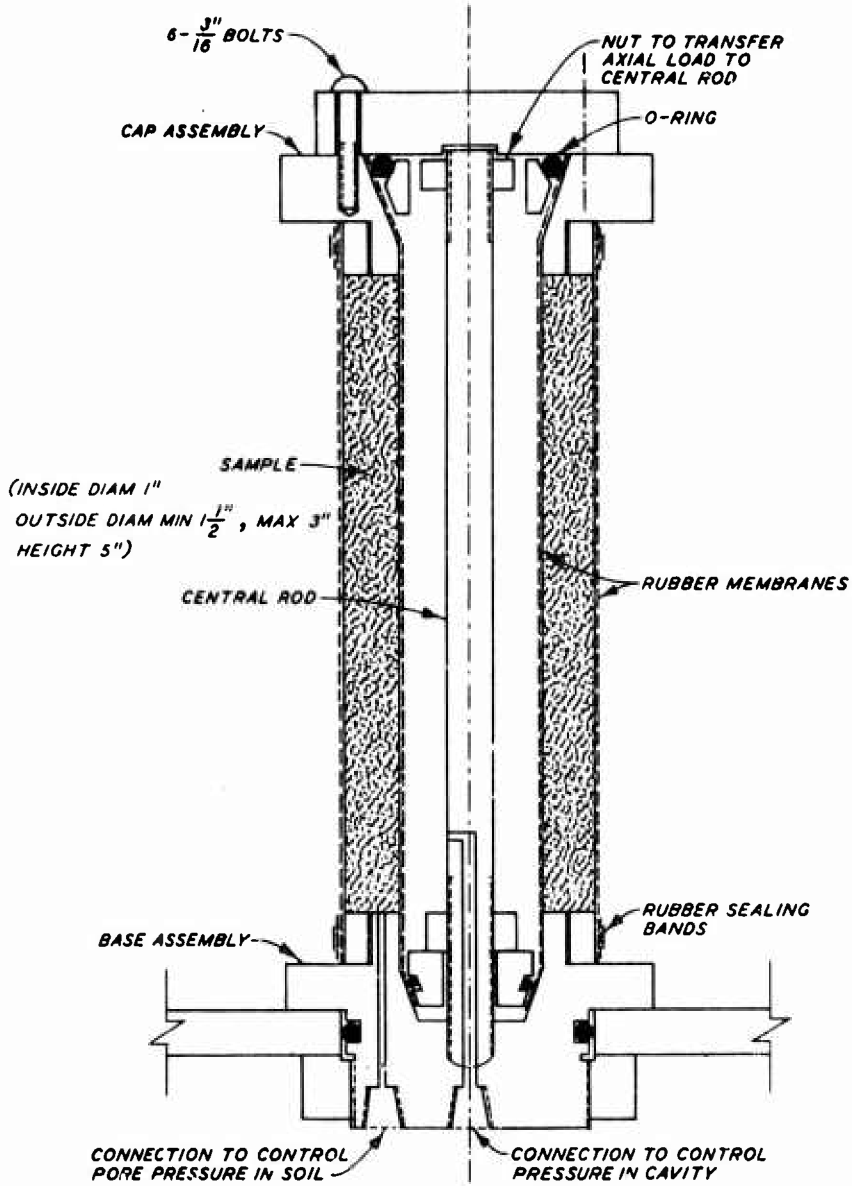


Fig. 11. Hollow cylinder plane strain apparatus

specimen placed between two rubber membranes and covered with a sealing cap. The specimen was contained inside a pressure chamber similar to that of the conventional triaxial cell. The sealing cap was machined to a special shape in order to hold an outside and inside rubber membrane around the specimen. The stresses applied in the test consisted of inside pressure σ_1 , outside pressure σ_o , and axial stress σ_a . As a result of this loading, each element within the soil specimen was subjected to three orthogonal stresses: radial stress σ_r acting along the radial direction; tangential stress σ_θ acting along the circumferential direction; and axial stress σ_a . Plane strain conditions were created by connecting the sealing cap with the base, thus restricting axial movement. Under plane strain condition, the axial stress was equal to σ_2 , the radial stress was equal to σ_1 , and the tangential stress was equal to σ_3 . In this apparatus, the value of σ_2 is not known, and the stress distribution within the specimen is not uniform.

Summary and Conclusions from Previous Studies

26. The previous discussion was a review of some of the plane strain shear devices that have been used in testing soil, and a summary of these devices is presented in table 1. The majority of these devices are only research tools, and none have been developed enough to be used efficiently and economically for routine testing. All the above-mentioned plane strain apparatus, with the exception of those for the Comisión Federal de Electricidad, were designed to test soil specimens under relatively low stresses. Currently, the Waterways Experiment Station has undertaken a study of the effect of different stress systems on the behavior of cohesionless soil under high confining pressure. Therefore, it was necessary to build a plane strain apparatus for testing soil under high confining pressure with the capability of measuring the stresses and/or controlling the strains during the test.

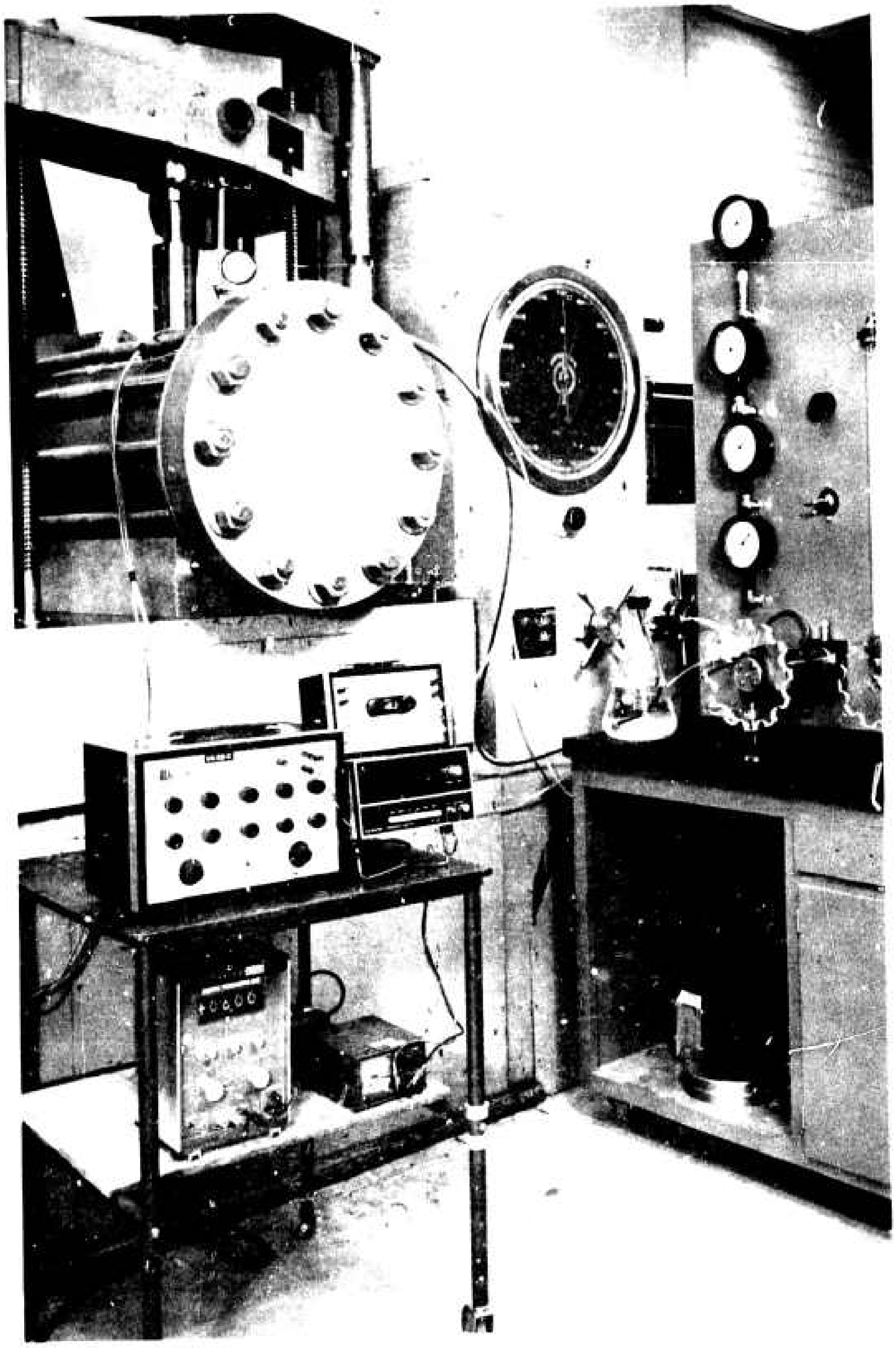
PART III: APPARATUS DEVELOPED BY WES

27. The new WES apparatus, shown in fig. 12, is similar to the apparatus developed by the author at the Georgia Institute of Technology[17] and is based on the concept of the Imperial College apparatus.[12] The unit accepts a specimen 2 in. wide and about 5 in. high. With the internal components initially fabricated, the length of the specimen is 16 in.; however, additional internal parts can be made to accommodate specimens with lengths from 5 to 20 in. The specimen is encased vertically between a rigid cap and base by a rubber membrane. Fluid pressure acts on the membrane within the pressure chamber to produce the minor principal stress. A ram entering the top of the pressure chamber acts on the rigid cap to produce the major principal stress. A hydraulic jack inside the pressure chamber acts on rigid vertical plates against the ends of the specimen to produce the intermediate principal stress required to maintain a plane strain condition, that is, to prevent changes in the length of the specimen during shear. While the compression chamber is designed for a maximum internal pressure of 5000 psi, all other components were initially fabricated to accommodate a maximum chamber pressure of 1000 psi.

Pressure Chamber

28. The cylindrical shell of the pressure chamber, as shown in fig. 13, is a steel tube, 13 in. in inside diameter and 34 in. long with a wall thickness of 2 in. At the top of the cylindrical shell and midway between the ends, a circular hole, 3-1/2 in. in diameter, is cut to fit the ram housing. The shell has six threaded holes for hydraulic and electrical connections. For low confining préssures, air is used as the chamber fluid, while for high confining pressures, silicone oil, General Electric Type SF-96(200), is used as chamber fluid.

29. Two circular end cap plates made of high tensile steel are placed around the ends of the cylindrical shell during the application



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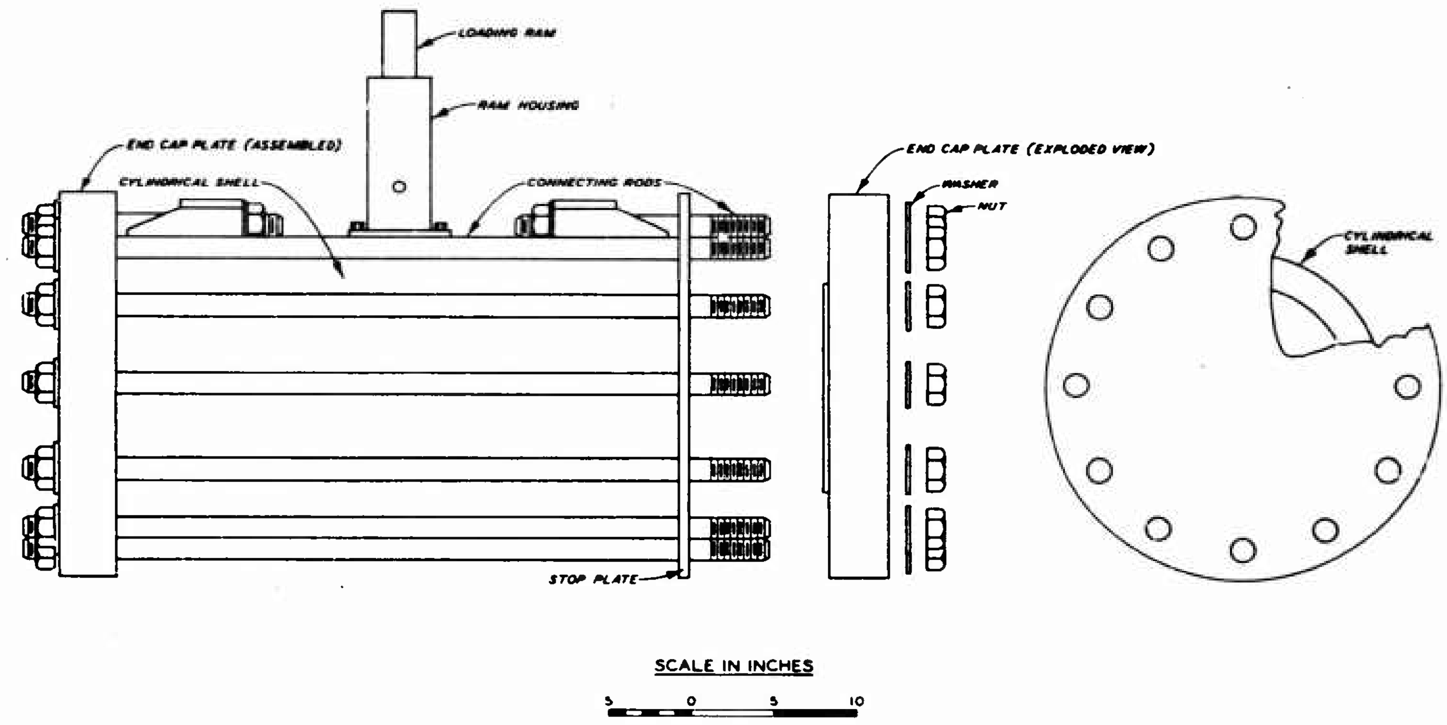


Fig. 13. Pressure chamber assembly

of pressure. Each plate is provided with a circular groove to fit a 1/4-in. pressure seal O-ring. Each end cap plate is provided with twelve 1-1/2-in. holes equally spaced around the center for the connecting rods. One end cap plate is attached firmly to the end of the cylindrical shell by the connecting rods, while the other end cap plate can easily be moved back and forth by means of a 2-ton chain hoist.

30. Twelve rods threaded at the ends and provided with nuts are used to attach the end cap plates tightly to the cylindrical shell to form the pressure chamber. Each rod is 1-3/8 in. in diameter and has a yield stress of 135,000 psi.

31. The ram housing assembly, shown in fig. 14, comprises the loading arrangement by which the axial load can be applied to the soil specimen with minimum friction. The loading ram is made of case-hardened steel, 2 in. in diameter and 18 in. long. The upper end of the ram is seated in a special fitting arrangement attached to the crossbeam of the loading machine. The lower end of the ram has a hemispherical shape that can be seated in a matching depression located at the center of the loading cap. The travel distance of the loading ram is sufficient to permit axial strain up to 40 percent in the tested specimen.

32. The loading ram is surrounded by a stainless steel housing, 3 in. inside diameter, 11-1/16 in. long, and 3/8 in. thick, which is made strong enough to give the loading ram sufficient stability against buckling. The ram housing is provided with two sets of 4-in.-long ball race bushings to minimize friction around the loading ram. The two sets of ball race bushings are separated by a circular brass sleeve, 1 in. thick, provided with a 1/8-in. hole connected to a grease fitting. At the bottom of the ram housing, another brass bushing is used to hold the ball race bushings in position. Leakage from the pressure chamber is prevented by three O-rings. Two are recessed in the lower brass bushing; the first one is on the inside and in contact with the loading ram, and the second is on the outside and is in contact with the ram housing. The third O-ring is placed between the cylindrical shell and the ram housing base.

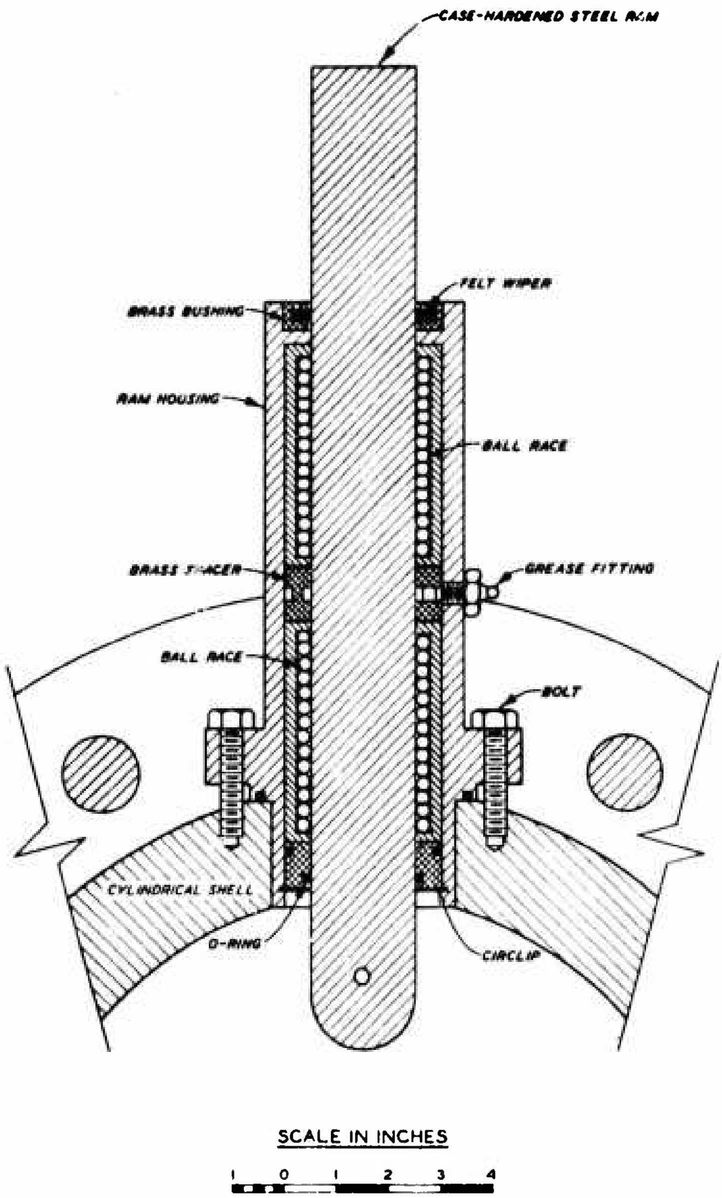


Fig. 14. Ram housing assembly

Vertical Loading Components

33. The elements of the apparatus that immediately surround the specimen within the compression chamber are shown in fig. 15; this figure shows a membrane-encased specimen with sensors and hydraulic lines attached ready to be placed in the compression chamber. The internal parts are individually indicated in the longitudinal view of a specimen shown in fig. 16 and more fully described in the lateral and longitudinal sections through a specimen shown in fig. 17. The discussion of these elements in the following paragraphs distinguishes components for applying the vertical load (loading cap, platens, etc.) from those used to apply the longitudinal load.

34. The main function of the loading cap is to transmit the axial load from the loading ram to the soil specimen. The loading cap is made of stainless steel machined into a prismatic tee, 16 in. long and 3-1/2 in. in height with a width of 2-1/2 in. at the top and 2 in. at the bottom. The loading cap is provided with six holes: one is to permit passage of the volume-change lead from the specimen to the pressure chamber; four holes are symmetrically spaced around the center for the connecting bolts; and the sixth hole is machined in the shape of a tee and is inclined at 60 deg from the vertical line. The stem of the tee is 1/8 in. in diameter and ends with a 1/4-in. male connection; the flange is made 3/8 in. in diameter to contain two small pistons. Each piston is provided with two pressure seal O-rings and a small screw to hold the lateral strain sensor against the specimen during consolidation. The loading cap is provided with a tension connector, which consists of two L-shaped brackets having a cylindrical surface on the inside to fit the loading ram. Two 1/4-in. holes are made in the brackets, and they are in line with the hole at the end of the loading ram when the loading cap and the ram are brought into contact.

35. The soil specimen is bounded at the top and bottom by two plates referred to here as platens. The upper platen is made of stainless steel, 16 in. long, 2 in. wide, and 3/4 in. thick, with a rectangular

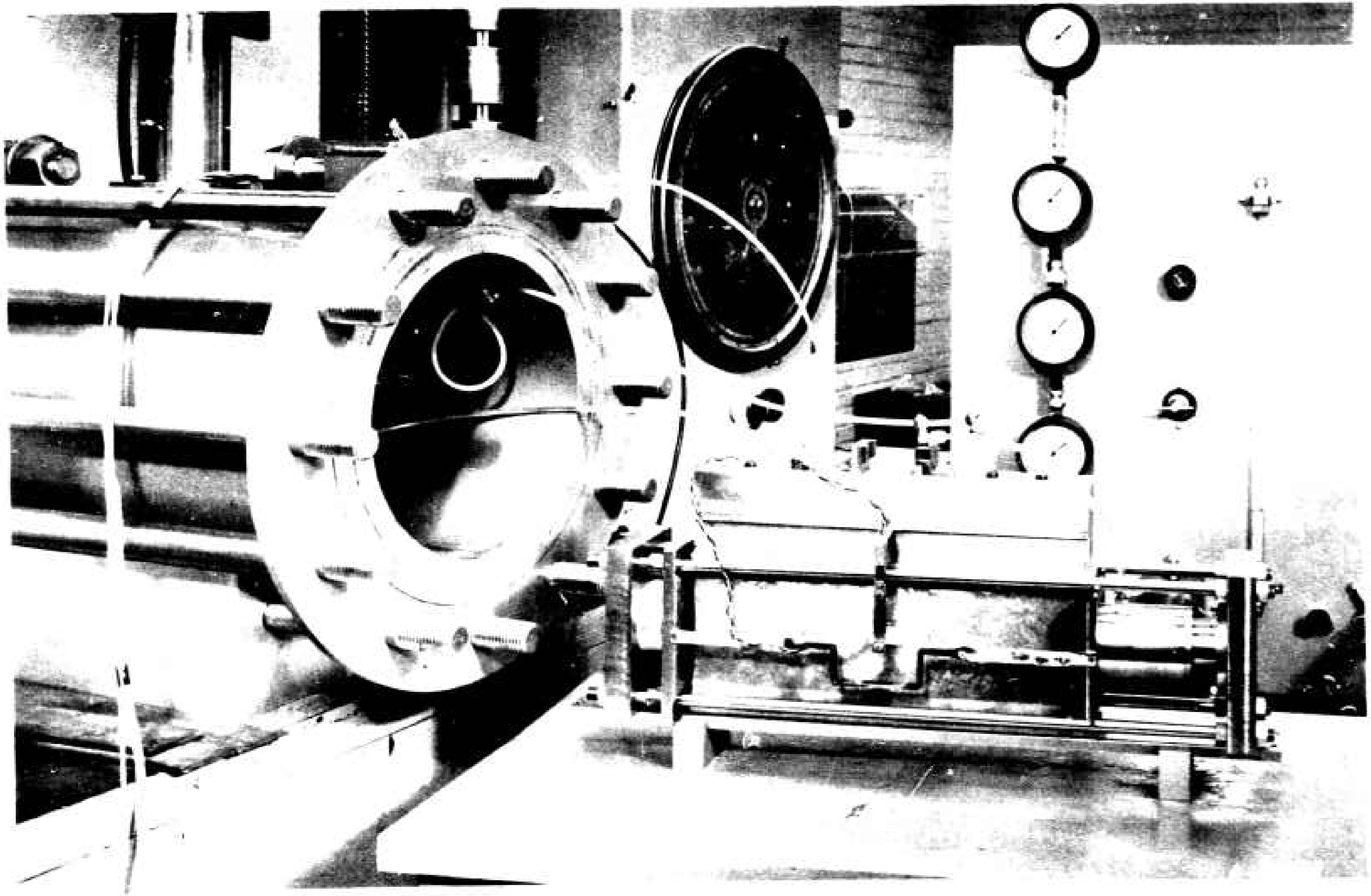


Fig. 15. Plane strain specimen assembled within internal components of apparatus ready to be placed in pressure chamber

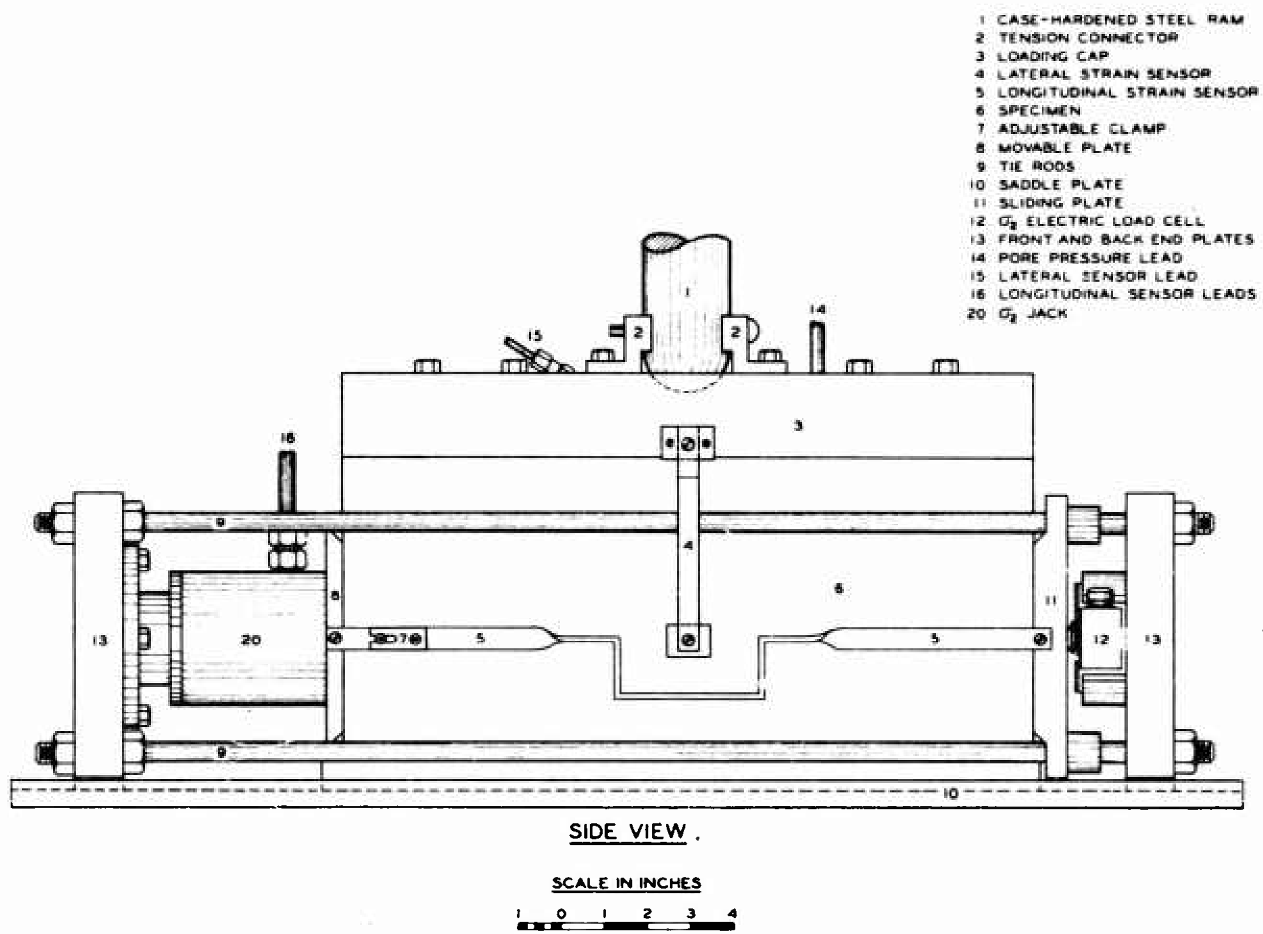


Fig. 16. Longitudinal view of specimen showing internal parts of apparatus

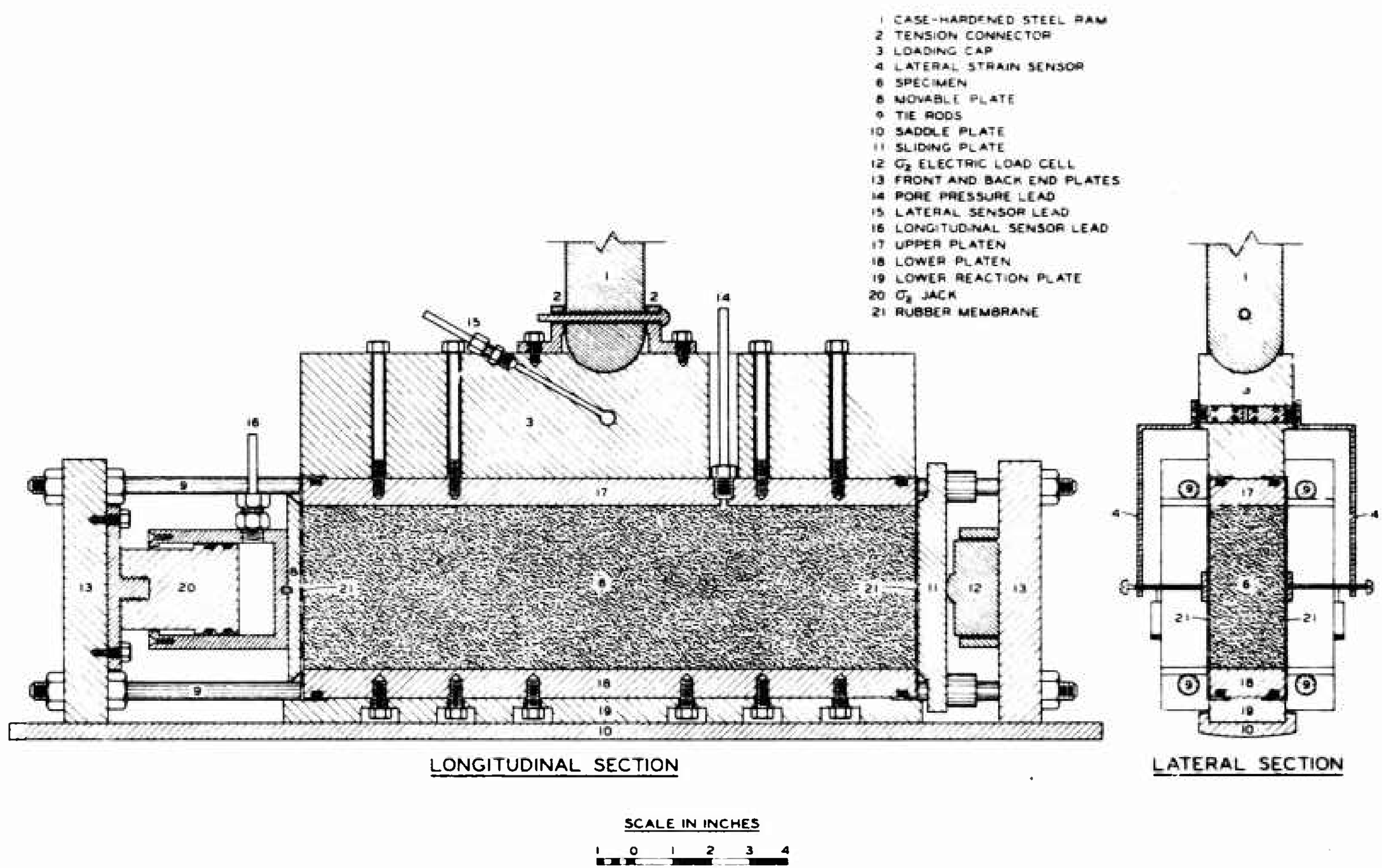


Fig. 17. Sections through plane strain specimen

groove machined along the edges of the surface facing the loading cap, as shown in fig. 18, and provided with a 1/4-in. pressure seal O-ring recessed inside the groove. Four threaded holes have been machined in the surface to receive 5/16-in. bolts that connect the upper platen to the loading cap. After the soil is placed inside the mold, the edges of the rubber membrane are squeezed between the upper platen and the loading cap by tightening the bolts so that a positive watertight pressure seal can be provided to the specimen. Along the center line of the platen surface that faces the specimen, a rectangular groove 3/16 in. wide, 1/32 in. deep, and 14 in. long has been cut and filled with two layers of No. 100 mesh screen wire to act as a filter for the pore fluid.

36. The lower platen is made similar to the upper platen with two exceptions: first, the drainage screen is eliminated since the specimen is drained only from the top, and second, six threaded holes instead of four were machined on its lower surface to fit 5/16-in. bolts. These bolts are used to connect the lower platen to the reaction plate, with the lower edge of the rubber membrane between the two; thus a positive watertight seal can be provided to the specimen at its lower end.

37. Two Teflon sheets are placed between the soil specimen and the platens to minimize end restraint that can be imposed by the platens on the soil specimen during the test. Each Teflon sheet is 16 in. long, 2 in. wide, and 1/32 in. thick and was cut into 1/4-in.-wide strips in the longitudinal direction. This method is found to be effective in reducing end restraint, since the coefficient of friction between the Teflon and the polished steel is much lower than that between the soil and the polished steel. It was observed during the early stages of plane strain testing that the Teflon strips helped greatly in creating uniform lateral deformation in the soil specimen under test.

38. The lower reaction plate serves as a base on which the soil specimen and the surrounding components rest. It is made of stainless steel plate, 16-5/8 in. long, 5/8 in. thick, and 2 in. wide, and provided with six holes symmetrically spaced around the center. The reaction plate

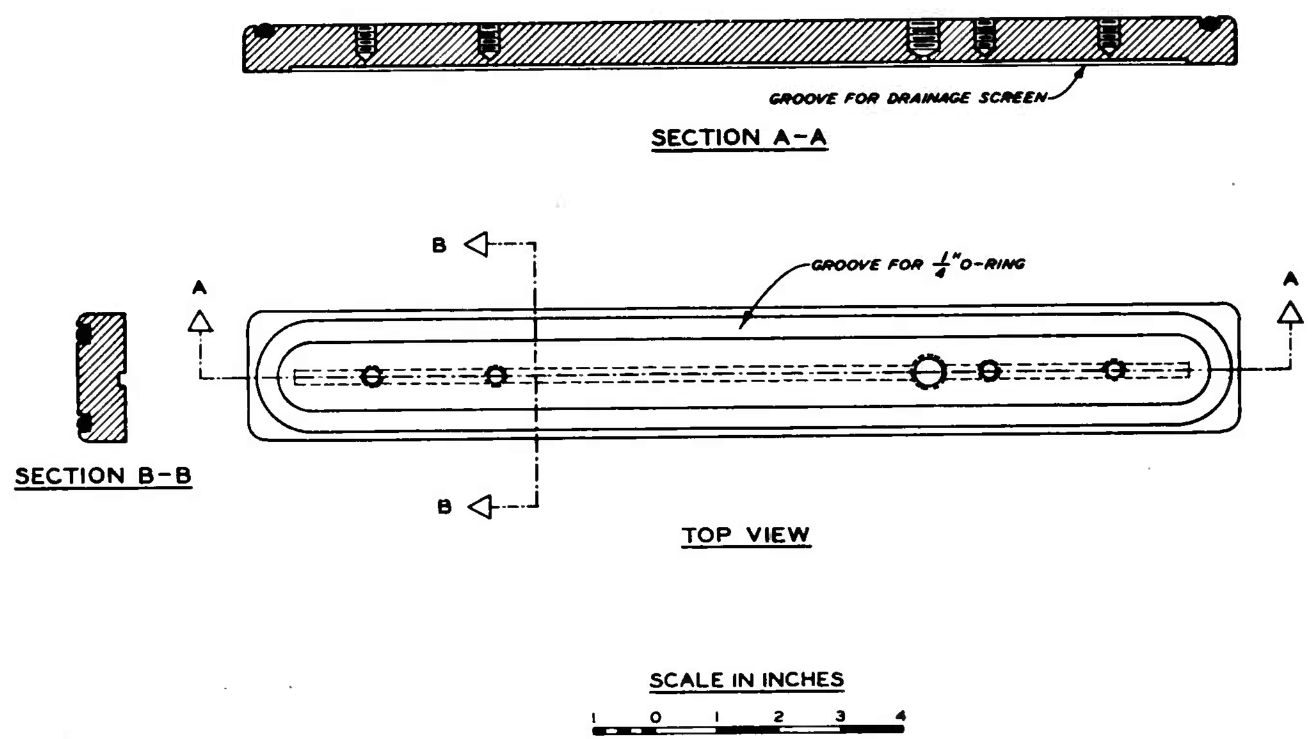


Fig. 18. Details of the upper platen

is also used to provide a watertight seal for the soil specimen when the lower edge of the rubber membrane is squeezed against the lower platen.

39. The saddle plate is made of stainless steel, 2-17/32 in. wide, 29 in. long, and 5/8 in. thick, with its lower surface curved to match the inside surface of the cylindrical shell. The upper surface of the saddle plate is machined into a rectangular channel 1/4 in. deep and 2-1/32 in. wide to form a cradle for the reaction plate and the rest of the components surrounding the specimen. The saddle plate is positioned inside the pressure chamber by two locating pins placed close to the ends to match the two holes drilled inside the cylindrical shell.

40. The lateral strain sensor, shown in fig. 17, is made of oil-drawn steel strips similar to the longitudinal strain sensor, 1/2 in. wide and 1/8 in. thick. Each strip is bent into a Z shape, with one end screwed to a small piston in the loading cap while the other end is provided with a 2-in.-long adjustable screw. The end of the adjustable screw is seated on a small aluminum plate, 1-1/2 in. long and 1 in. wide, that remains in contact with the specimen during one-dimensional consolidation. The Z frames are provided with four strain gages to form a temperature-compensating bridge that can be used to sense any movement in the lateral direction of the specimen during consolidation.

Longitudinal Loading Components

41. To produce the intermediate principal stress, a horizontal force is applied to both ends of the specimen by a frame, shown in fig. 15, consisting of two 1-in.-thick stainless steel end plates connected by four 1/2-in.-diam stainless steel tie rods. The end plates rest on the saddle plate and are free to move longitudinally, though each is restrained from lateral movement by a projection on the bottom that fits the channel in the saddle plate. This horizontal loading frame provides only a reaction for the force applied to each end of the specimen; elongation of the tie

rods under load in no way affects the prevention of longitudinal deformation of the specimen.

42. Bearing against the membrane of one end of the specimen is a 3/4-in.-thick stainless steel plate, called the sliding plate in figs. 16 and 17. The rectangular sliding plate is suspended from the tie rods of the loading frame by four Thomson linear-motion ball bushings. The surface of this plate in contact with the membrane is highly polished and has sufficient height and width to cover the end of the specimen completely as it deforms laterally during shear. The longitudinal force is measured by an electrical load cell (BLH Type C2M1C, 10,000-lb capacity) held on the face of one end plate so its spherical sensing button bears at the center of the unpolished face of the sliding plate. The small contact area of the button ensures that the full chamber fluid pressure acts on the ends of the specimen in addition to the force measured by the electrical load cell.

43. Against the opposite end of the specimen bears a 3/8-in.-thick stainless steel plate called the movable plate. The rectangular surface in contact with the membrane has the same dimensions as those of the sliding plate and is also highly polished. However, the movable plate simply rests on the two lower tie rods of the loading frame. A hydraulic jack attached to the inside face of the end plate acts against the outer unpolished face of the movable plate to produce the longitudinal force, which is measured at the opposite end of the specimen by the load cell.

44. Surfaces of the sliding and movable plates in contact with the specimen are coated with a thin layer of silicone grease to minimize friction that might develop during the application of the axial load. The coefficient of friction between the rubber membrane and the polished stainless steel, determined using a direct shear box (see Appendix A), is 0.024. It is possible to apply the intermediate principal stress σ_2 to the soil specimen by delivering oil under pressure to the hydraulic jack, which, in turn, transmits the pressure to the specimen via the movable plate. However, the apparatus was designed to measure the intermediate principal stress as dictated by the plane strain conditions rather

than applying preassigned intermediate principal stress. The friction forces that developed at the ends of the specimen due to the application of σ_2 were evaluated empirically, as shown in Appendix B.

45. Connecting the movable plate with the sliding plate are the two longitudinal strain sensors, one on each side of the specimen. Each sensor is made of oil-drawn steel, 1/2 in. wide and 1/8 in. thick, bent with a rectangular loop in the middle as shown in fig. 15. The length of each sensor can be adjusted by a small clamp near one end. Two strain gages are fixed to each sensor by Eastman 910 cement, and the four gages are wired to form a temperature-compensating bridge. The wires from the longitudinal strain sensors are joined with those from the lateral strain sensors to form a single cable that passes through the shell of the compression chamber by a sealed connector.

46. During the shear stage of a test, the sliding and movable plates, despite their names, neither slide nor move. Any tendency for the distance between these plates to change, as detected by the longitudinal strain sensors, is immediately eliminated by changing the longitudinal force with the hydraulic jack. As can be seen from the calibration of the strain sensors presented in Appendix C, an elongation of the longitudinal strain sensor equal to 0.001 in. produced a change in voltmeter reading of 170 microvolts. It was possible, during any test, to adjust the longitudinal force so that voltmeter reading never changed by more than 5 microvolts. Thus, the distance between the sliding and movable plates never varied by more than 0.00003 in., which is less than the error caused by the compression of the membrane covering the ends of the specimen.

Hydraulic Systems

47. As shown schematically in fig. 19, three separate pressure-control systems are required to operate the apparatus. The first is the system

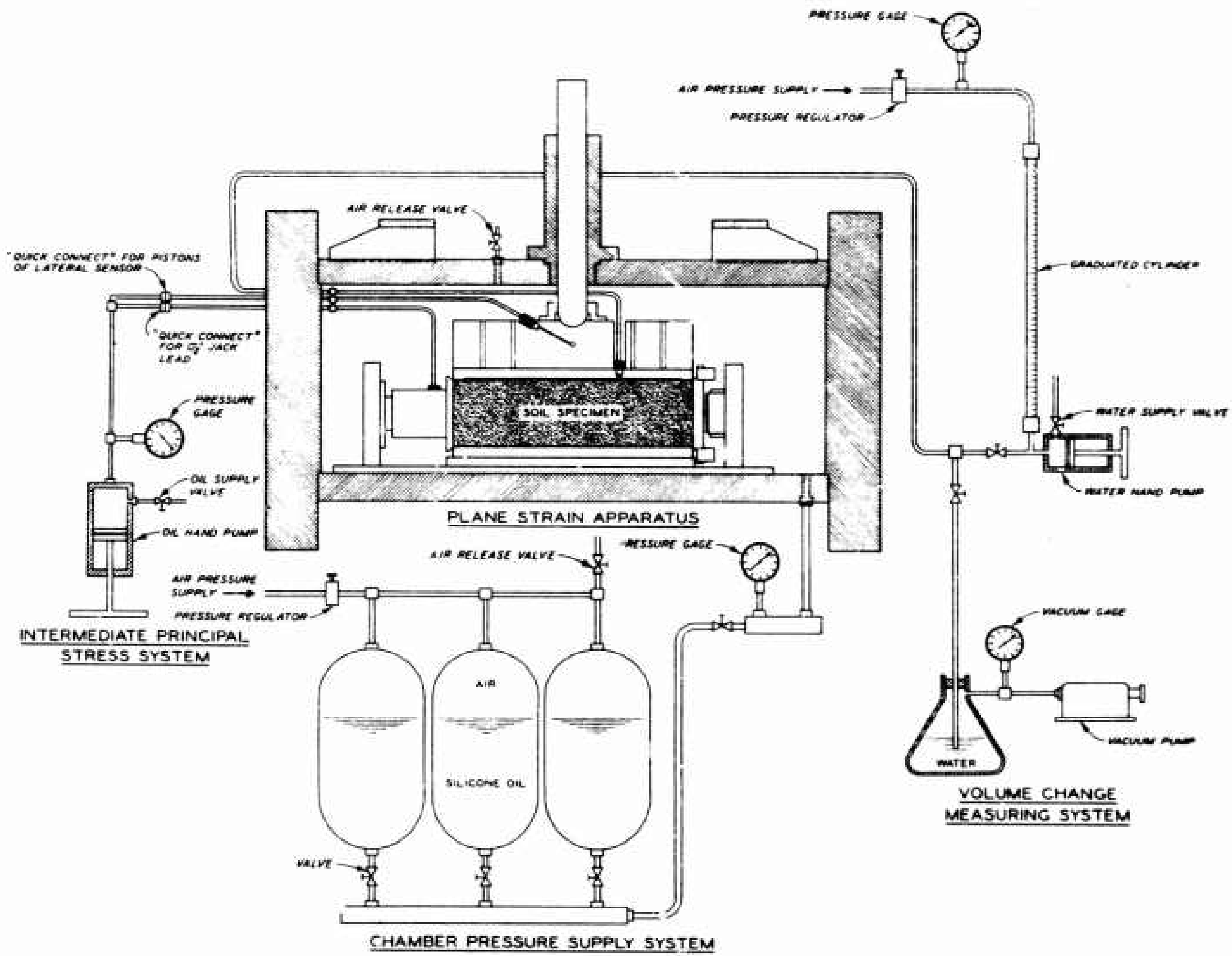


Fig. 19. Schematic drawing of hydraulic systems

to fill the compression chamber with fluid and to apply the desired pressure to this fluid. Three large tanks are connected in parallel to provide the quantity of fluid required. For low-pressure tests (say less than 1,000 psi), air is applied through a pressure regulator to the fluid remaining in the tanks to develop the chamber pressure. For high-pressure tests, a separate source of pressure would have to be connected to the chamber in order to bypass the three tanks.

48. The second hydraulic system operates the jack inside the compression chamber applying the longitudinal force to the specimen. This pressure is manually controlled by a screw pump. A second line from the pump connects to the loading cap and permits applying pressure to the two pistons holding the lateral strain sensors so these sensors can be moved away from the specimen at the end of the consolidation stage.

49. The third system provides drainage of water from the specimen and, with modification, would permit measurement of pore water pressures. A burette is used to measure changes in specimen volume, with a screw pump connected to adjust the water level in the burette. Back pressure is applied by air through a pressure regulator to the water surface in the burette. A separate line connects a source of vacuum required to support a specimen of cohesionless soil until chamber pressure is applied.

Instrumentation

50. The vertical force applied through the cam to develop the major principal stress is measured by the universal testing machine; the Tinius Olsen 60,000-lb machine used has an accuracy of $\pm 1/2$ of one percent. The load cell for measuring the longitudinal force produced by the intermediate principal stress has an accuracy of $\pm 1/10$ of one percent. The chamber pressure, which equals the minor principal stress, is measured by a Bourdon tube test gage with an accuracy better than $\pm 1/4$ of one percent.

51. Vacuum and back pressure applied to the specimen pore water were also measured with test gages accurate to within ±1/4 of one percent. Specimen volume changes were measured with a 100-ml burette graduated every 0.2 ml.

52. Vertical deformation of the specimen, used for the computation of axial strain, is measured by the movement of the ram using a dial indicator graduated every 0.001 in. Calibration data for the lateral and longitudinal strain sensors are presented in Appendix C. The calibration of these sensors is checked periodically.

PART IV: DEMONSTRATION TESTS

Material

53. The performance of the new plane strain apparatus was evaluated by testing medium dense and dense crushed basalt under 60-psi effective confining pressure. Crushed Napa basalt was chosen for this purpose simply because the deformation characteristics of the material have already been studied[18] in the conventional triaxial apparatus, and its properties are well established. The material was obtained from the Basalt Company's Blue Rock Quarry at Napa, California. The crushed basalt used can be described as highly angular with elongated or plated particles. It consists of plagioclase, diopside, augite, and traces of montmorillonite clay mineral. The major physical properties of the material as determined by standard procedures[19] are: specific gravity 2.9; maximum void ratio 0.958; minimum void ratio 0.535; and unconfined compressive strength of the intact rock 25,000 psi. The different sizes c the crushed basalt were mixed prior to the test to form a straight-line gradation curve extending from No. 3 to No. 30 U. S. Standard Sieve. This type of gradation curve was first adopted by the U. S. Army Engineer Division Laboratory, South Pacific,[19] and is followed in this study.

Preparation of the Specimen

54. A proper amount of the dry crushed basalt as dictated by the initial relative density desired for the test was accurately measured. The different sizes of the material that composed the specimen were mixed thoroughly and then flooded with distilled water in a shallow pan. The mixture was boiled for about 10 minutes in order to get rid of any air bubbles that might have adhered to the soil grains, then was allowed to cool to room temperature. The rubber membrane, manufactured as described in Appendix D, was checked for holes and imperfections. The lower edge

of the rubber membrane was then sealed between the lower end platen on the inside and the lower reaction plate on the outside.

55. The specimen mold, as shown in fig. 20, consisted of four aluminum plates connected together by bolts and wing nuts. This mold was assembled around the rubber membrane and allowed to rest on the lower reaction plate. The rubber membrane was stretched evenly inside the aluminum plates to give the specimen a prismatic shape and its upper end was rolled around the upper edges of the specimen mold. The thin Teflon sheet, which was stripped longitudinally, was spread on the lower platen, and the whole assembly was positioned properly inside the saddle plate. Distilled water was poured inside the specimen mold to ensure that no air bubbles were trapped between the rubber membrane and the lower platen before starting the actual preparation of the soil specimen.

56. The material that had been prepared for the test was placed with a small scoop inside the specimen mold, which always contained sufficient water to cover the material. The material was spread in layers 1/2 in. thick. A dense specimen was prepared by vigorously vibrating each layer with a mechanical vibrator, while a medium-dense specimen was prepared by gently vibrating the sides of the specimen mold. The mechanical vibrator used is 3/4 in. Air Cushioned, made by Cleveland Vibratory Company. Extra care was taken in compacting and leveling the last layer of soil before covering its surface with the upper stripped sheet of Teflon. The upper platen was gently lowered inside the specimen mold to rest on the Teflon sheet, and the edge of the rubber membrane was stretched and turned over it. The loading head was then placed in its proper position, and the rubber membrane was sealed by tightening the bolts that connect the upper platen with the loading head. Vacuum was applied to the soil in order to make the specimen rigid enough to be self-supporting. Finally, the wing nuts were loosened, and the specimen mold was gently removed from the specimen, as shown in fig. 20. Several measurements of the height, the width, and the length of the specimen at different locations were recorded, and the average values were considered in density and stress computations.

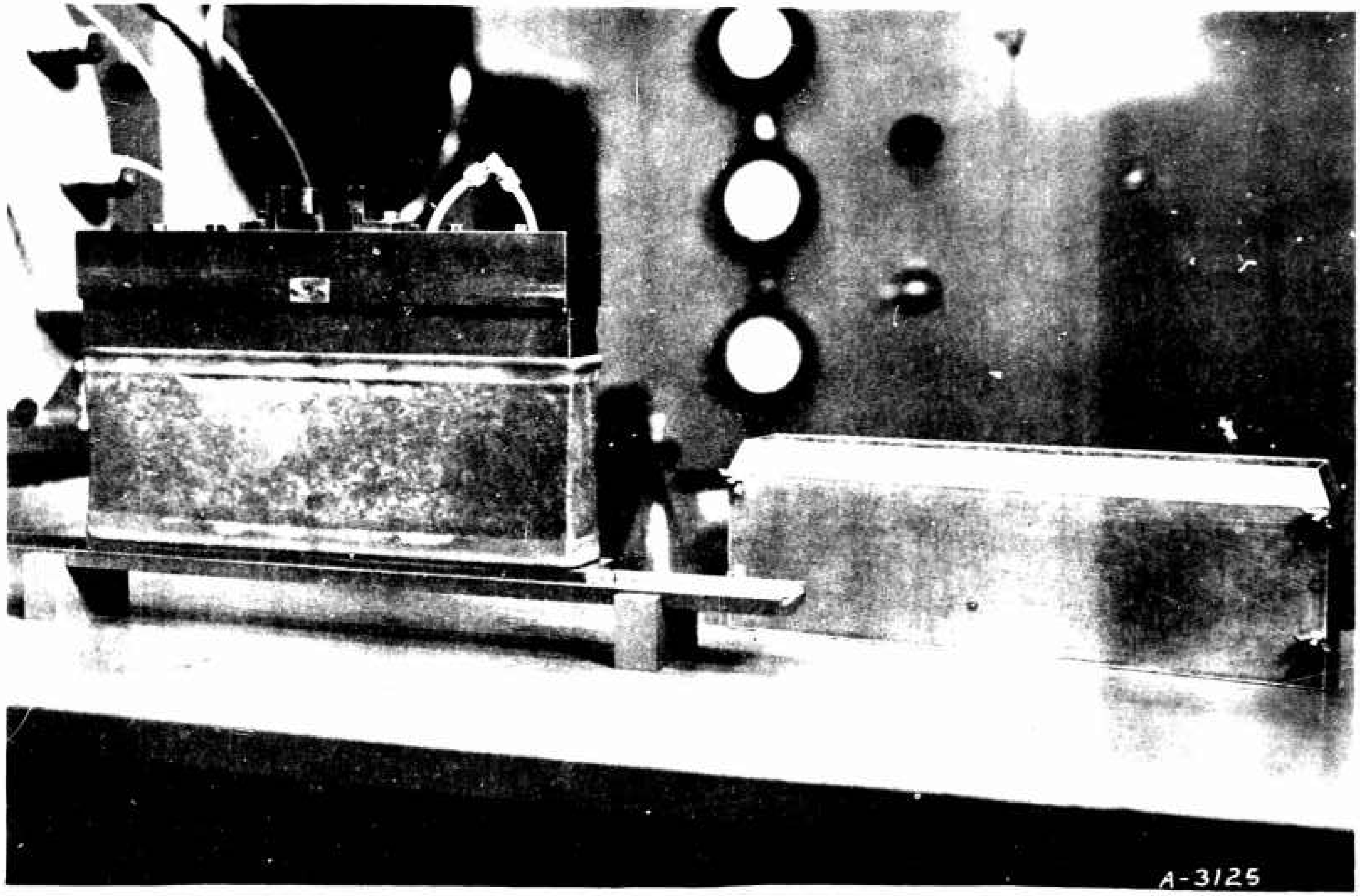


Fig. 20. Plane strain specimen under vacuum sealed within rubber membrane; specimen mold at right

57. A thin film of silicone grease was applied to surfaces of the movable and sliding plates in contact with the specimen to reduce the friction that might develop during the test. The intermediate principal stress system, which consists of the hydraulic jack, the load cell, the movable plate, the sliding plate, the tie rods, and the end plates, was carefully assembled around the specimen. In order to take the slack from the intermediate principal stress system and to ensure full contact with the specimen, the tie rod nuts were tightened gently and evenly until the load cell started to register a small load. The length of the longitudinal sensor was adjusted with respect to the length of the specimen and its ends were fixed to the sliding and movable plates. If it was desired to consolidate the specimen, one-dimensional consolidation (i.e., K_o consolidation), the lateral sensor had to be fixed properly around the specimen. The electric connection was secured, and all the measuring and controlling devices were checked for perfect performance before transferring the specimen inside the pressure chamber. Finally, the soil specimen and the surrounding components were placed inside the pressure chamber, as shown in fig. 21, and the end cap plate was fixed tightly in position.

Consolidation Stage

58. After the pressure chamber had been filled with fluid and the air release valve closed, the chamber pressure was raised while the vacuum applied to the pore water of the specimen was simultaneously decreased. When the chamber pressure equalled the previously applied vacuum and the pore water was at atmospheric pressure, back pressure was applied to the specimen through the burette. This was accomplished by the simultaneous increase of the pore pressure on the inside and the chamber pressure on the outside of the specimen, by the same amount, keeping the effective stress unchanged. Back pressure of 20 psi was used throughout the test program. The voltage readings of the longitudinal and lateral strain sensors were set to read zero on the digital output

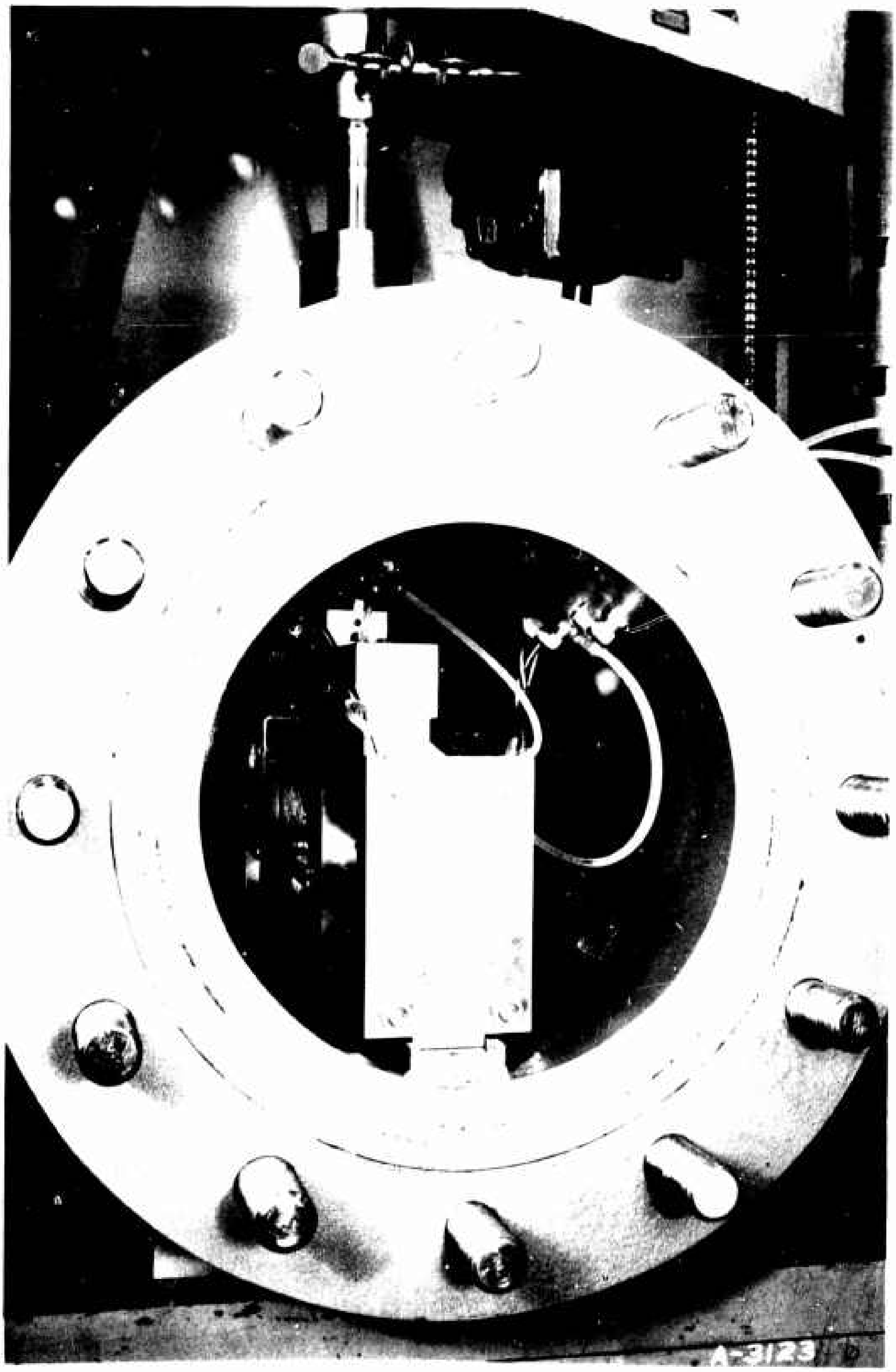


Fig. 21. Plane strain specimen and internal components inside pressure chamber

reader. The initial readings of the load cell, the volume change device, and the dial gage for the measurement of the axial deformation were recorded.

K_o consolidation

59. Under K_o consolidation, the soil specimen was allowed to consolidate under zero lateral deformation. The loading procedure consisted of increasing the chamber pressure by a small amount (10 psi used in the test), which caused a very small but detectable reduction in the dimensions of the specimen. The decrease in the width of the specimen caused a change in the electrical resistance of the lateral strain sensor, which, in turn, caused the reading on the digital output reader to increase in the negative direction. The same thing also happened to the reading of the longitudinal strain sensor; however, only the lateral strain sensor was used as the control during consolidation. The axial load was then increased at a constant rate of strain of 0.003 in. per min. The increase in the axial load caused the soil specimen to increase in the lateral dimensions. The small increase in the width of the specimen activated the lateral strain sensor and caused the digital output reader to increase in the positive direction. At the moment the reading showed zero, a set of readings, which included the level of water in the volume-change device, the axial load, the chamber pressure, the back pressure, the load cell, and the axial deformation, were recorded. The chamber pressure was then increased to the next pressure increment, and the process was repeated until the consolidation pressure reached the preassigned value. After consolidation of the specimen was completed, the lateral strain sensor was disconnected by applying pressure to activate the small pistons on which the lateral sensor was mounted.

Isotropic consolidation

60. In the isotropic consolidation test, the chamber pressure was increased in convenient increments; 10-psi increments were used throughout the test. The second pressure increment was resumed when the flow of

pore water from the previous increment had stopped completely. After each pressure increment, readings of the volume change, chamber pressure, and axial strain were recorded. The increase in the chamber pressure was continued until the preassigned consolidation pressure was reached. At the end of consolidation, the movable end plate was brought into contact with the specimen, and the specimen was ready for the shear stage.

Shear Stage

Drained shear test

61. During the drained shear test, the axial load was increased at a constant rate of strain of 0.004 in. per min (strain control). The increase in the axial load caused the soil specimen to deform in the lateral direction. Longitudinal deformation, however, was prevented by continuous adjustment of the hydraulic jack with the manual pump outside the cell as required to maintain a zero reading of the longitudinal strain sensor. Readings of the axial load, load cell, volume-change device, chamber pressure, back pressure, and the axial deformation dial gage were recorded at each 0.025 in. of axial deformation. The test was stopped when the axial load started to decline or when it stayed constant during the increase of axial deformation. At the end of the test, the apparatus was dismantled, and the material was dried and sieved.

Undrained shear test

62. It is possible to shear the soil specimen under undrained condition with pore pressure measurements in the new plane strain apparatus. However, all the plane strain tests conducted so far have been on specimens sheared under drained conditions.

Reduction of Data

63. The computation of the data was programmed to the WES GE 427 computer; the program listing for the plane strain test is shown in Appendix E.

PART V: PRESENTATION AND DISCUSSION OF RESULTS

64. The performance of the new plane strain apparatus was evaluated by studying data obtained from plane strain tests on crushed basalt. The specimens were prepared at two initial relative densities, 70 and 100 percent, and were sheared under drained condition at maximum consolidation pressure of 60 psi. A summary of the results is presented in tabulated form in table 2.

Consolidation Phase

65. Under K_o consolidation, the lateral dimensions of a plane strain specimen remain unchanged. If the length and width remain constant, and assuming the material exhibits isotropic behavior during consolidation, the value of the minor principal effective stress σ_3' equals the value of the intermediate principal effective stress σ_2'. The value of K_o under one-dimensional consolidation is equal to the ratio of $\frac{\sigma_3'}{\sigma_1'}$ and should equal the ratio of $\frac{\sigma_2'}{\sigma_1'}$. The observed relationship between the stress ratios, i.e., $\frac{\sigma_3'}{\sigma_1'}$ and $\frac{\sigma_2'}{\sigma_1'}$, and axial strain ϵ_1 for the plane strain tests is illustrated in fig. 22a. The ratios $\frac{\sigma_2'}{\sigma_1'}$ and $\frac{\sigma_3'}{\sigma_1'}$ started from a value equal to one, which represents the initial isotropic stress condition to which the crushed basalt was subjected at the beginning of the test. These ratios decreased sharply at the beginning of consolidation; then they leveled off and remained almost constant until the end of consolidation. The value of $\frac{\sigma_2'}{\sigma_1'}$ was always slightly higher

Table 2

Summary of Demonstration Test Results

Test No.	At the Beginning of Test: Void Ratio e_i	At the Beginning of Test: Relative Density Dr_i %	At the End of Consolidation: Relative Density Dr_i %	At the End of Consolidation: σ_1' psi	At the End of Consolidation: σ_2' psi	At the End of Consolidation: σ_3' psi	At the End of Consolidation: K_o	At Failure: σ_1' psi	At Failure: σ_2' psi	At Failure: σ_3' psi	At Failure: ϕ' deg	At Failure: Axial Strain ϵ_1 %	At Failure: Volume Strain $\Delta V/V$ %	τ_{oct}/σ_{oct}
PSI 1	0.537	99.45	103.92	60.00	60.00	60.00	--	458.85	132.08	60.00	50.23	8.35	- 1.76	0.874
PSK 2	0.533	100.5	108.72	204.52	65.91	60.00	0.293	446.31	140.51	60.00	49.71	6.51	- 0.82	0.854
PSK 3	0.659	70.68	84.14	168.87	64.80	60.00	0.355	354.88	117.17	60.00	45.30	9.31	- 2.48	0.791
PSI 4	0.677	66.43	74.89	60.00	60.00	60.00	--	341.86	120.67	60.00	44.53	12.67	- 4.12	0.772

Note: PSI - plane strain isotropically consolidated specimens
PSK - plane strain anisotropically consolidated specimens

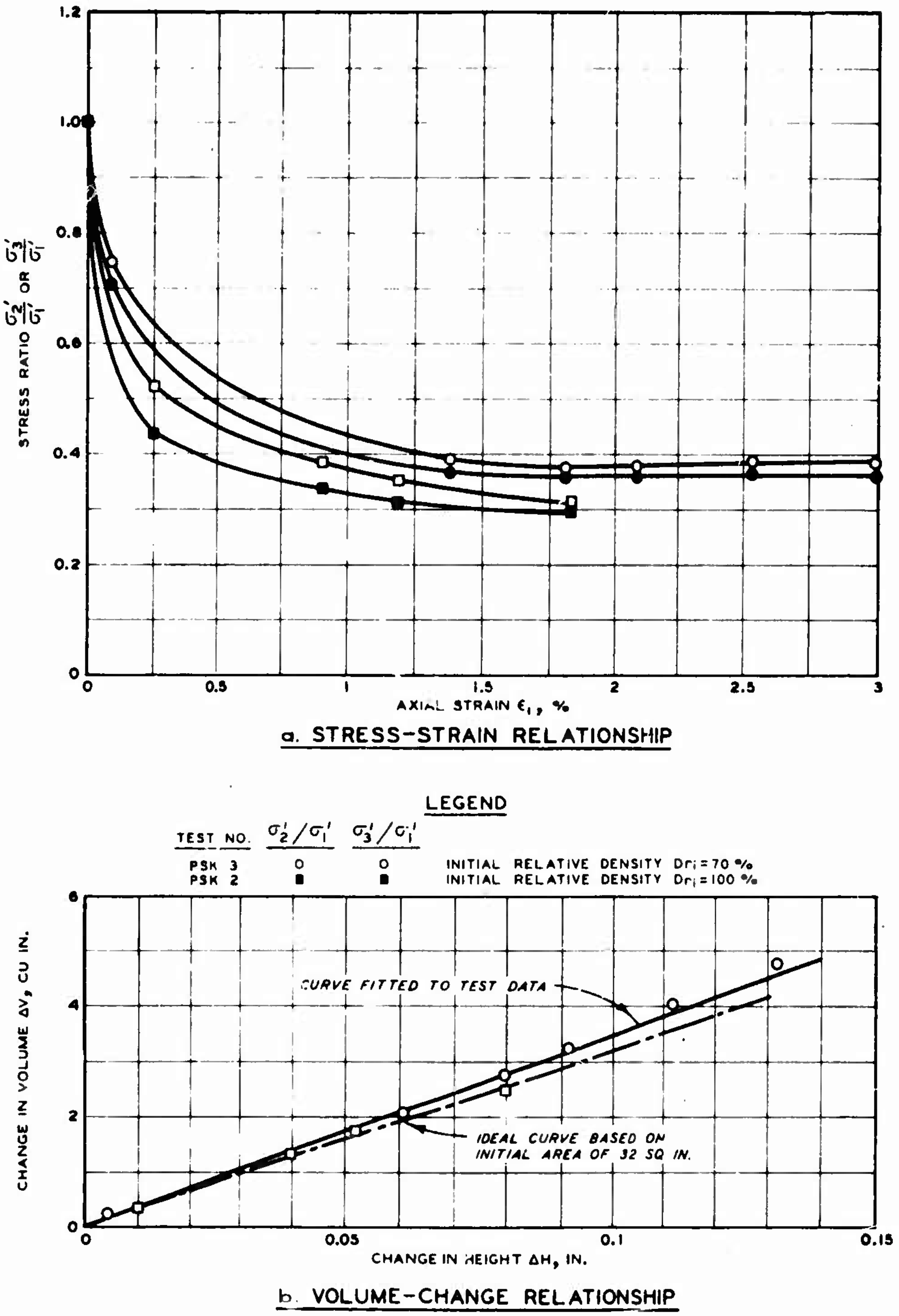


Fig. 22. Stress-strain and volume-change relationships during K_o consolidation for plane strain specimens

than the ratio of $\frac{\sigma_3'}{\sigma_1'}$ by almost a constant amount. The reason for this difference is not clear; however, it might be related to either the small amount of prestressing applied to the tie bars during the setting of the test or to the electronic digital reader of the load cell. The difference might also be related to boundary conditions associated with σ_2' and σ_3'. With regard to the initial relative density of the specimens, it can be seen that both ratios $\frac{\sigma_2'}{\sigma_1'}$ and $\frac{\sigma_3'}{\sigma_1'}$ are higher for medium-dense specimens than for dense specimens. Thus the value of K_o is higher for loose than for dense crushed basalt.

66. Since there is no change in the lateral dimensions of the specimen during K_o consolidation, volumetric strain is numerically equal to axial strain. The theoretical relationship between the change in the volume to the change in the height, shown in fig. 22b, should be a straight line passing through the origin, with a slope equal to the initial cross-sectional area of the specimen (32 sq in.). However, the slope based on measured values is slightly steeper than this value; this might be due to membrane penetration during applications of cell pressure.

Shear Phase

Stress-strain and volume change for K_o test

67. In this study the soil specimen was considered to be at failure when the major principal effective stress reached a maximum value and the axial strain at the failure point was equal to the failure strain. The stress-strain and volume-change relationships, at shear, for plane strain specimens consolidated under K_o consolidation are shown in fig. 23. The graphs show that σ_2' started at a value slightly higher than σ_3', and σ_1' started at a value equal to $\frac{\sigma_3'}{K_o}$. It is also shown that the variation

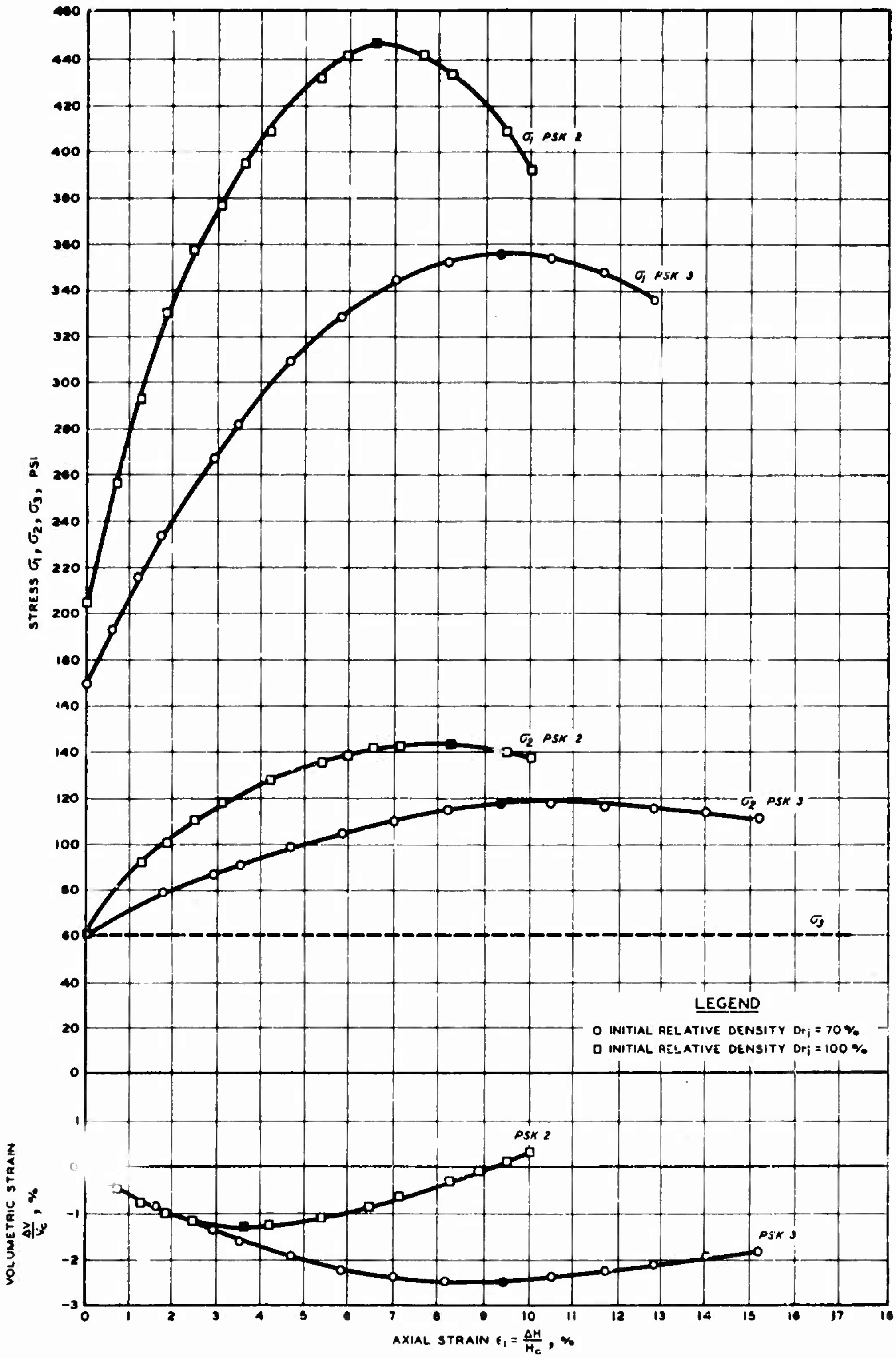


Fig. 23. Stress-strain and volume change relationships during shear for plane strain specimens consolidated under K_o condition

of σ_1' and σ_2' with respect to axial strain is relatively linear only at the beginning of the test and then starts to curve gradually until failure. It is of interest to note that σ_1' and σ_2' do not necessarily reach maximum values at the same time, and that after failure the rate of decline of σ_1' is much faster than σ_2'. Dense specimens have lower axial strain but higher σ_1' and σ_2' at failure than the medium-dense specimen. The failures of dense specimens were associated with rupture-type failure with a visible failure plane, but no failure planes were observed in the medium-dense specimens.

68. The volume change of the plane strain specimen was measured by the amount of water expelled during application of axial load. The volumetric strain at any point is considered to be the ratio of volume change to total volume of the specimen at the end of consolidation. Figure 23 shows the variation of volumetric strain versus axial strain; the general shape of the curve varies with placement density. It is also shown that specimens with initial relative density of 100 percent exhibit lower volumetric strain than specimens with initial relative density of 70 percent. The maximum volumetric strain for dense specimens occurs before failure, while for the medium-dense specimen, it occurs at failure.

Stress-strain and volume change for isotropic consolidated test

69. The stress-strain and volume-change relationships for plane strain specimens consolidated isotropically and sheared under drained condition are shown in fig. 24. These stress-strain curves show that the three principal effective stresses, σ_1', σ_2', and σ_3', started from the same point, but σ_1' and σ_2' increased rapidly at different rates of increase with axial strain, while σ_3' stayed constant. The dense specimen showed more linearity between σ_1' and σ_2' with respect to axial strain and also higher stresses than the medium-dense one. However, the axial strain at failure for medium-dense specimens was larger than for the dense specimen. Comparing the curves of fig. 24 with those plotted in fig. 23, it is seen that specimens with similar placement density behave differently

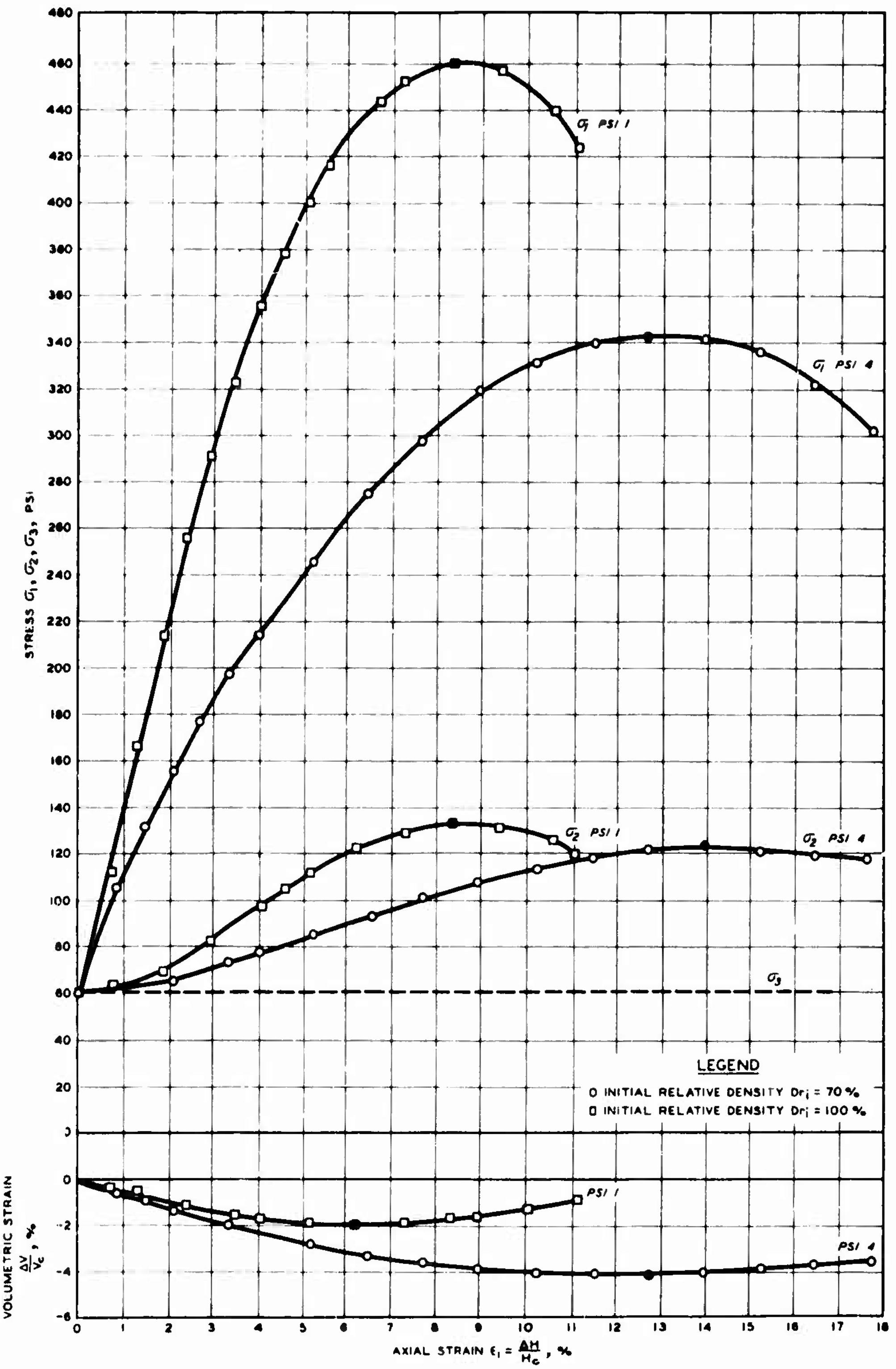


Fig. 24. Stress-strain and volume-change relationships during shear for plane strain specimens consolidated isotropically

for the two types of consolidation. Specimens with similar initial relative density have almost the same peak stresses, but isotropically consolidated specimens have larger volumetric strain during shear and higher failure strain than those consolidated under one-dimensional consolidation.

Shear strength parameters

70. When an external load is applied to cohesionless material, the load will be transmitted to the whole mass through the points of contact between the grains and relative movements of the grains will be in the direction of least resistance. The movement of the soil grains is always associated with shearing stresses that develop in the plane of movement. Such shearing stresses are directly proportional to the normal stresses acting on the same plane, and they can be related as

$$\tau = \sigma_n \tan \phi' \qquad (1)$$

where τ = shearing stress

σ_n = normal stress at the same point

ϕ' = effective angle of internal friction

Thus the shearing strength that any cohesionless material can withstand is greatly influenced by the angle of shear resistance. The conventional Mohr-Coulomb theory is used to evaluate the value of ϕ' as follows:

$$\phi' = \arcsin \frac{\sigma_1' - \sigma_3'}{\sigma_1' + \sigma_3'} \qquad (2)$$

Mohr's envelopes for plane strain tests in terms of effective stresses are shown in fig. 25. The results show that the method of consolidation in plane strain tests has little or no effect on the value of the angle of shear resistance.

71. Since Mohr's theory does not account for the value of σ_2 in evaluating ϕ', the strength of soil may be better presented in terms of octahedral normal stress σ'_{oct} and the octahedral shear stress τ_{oct}.

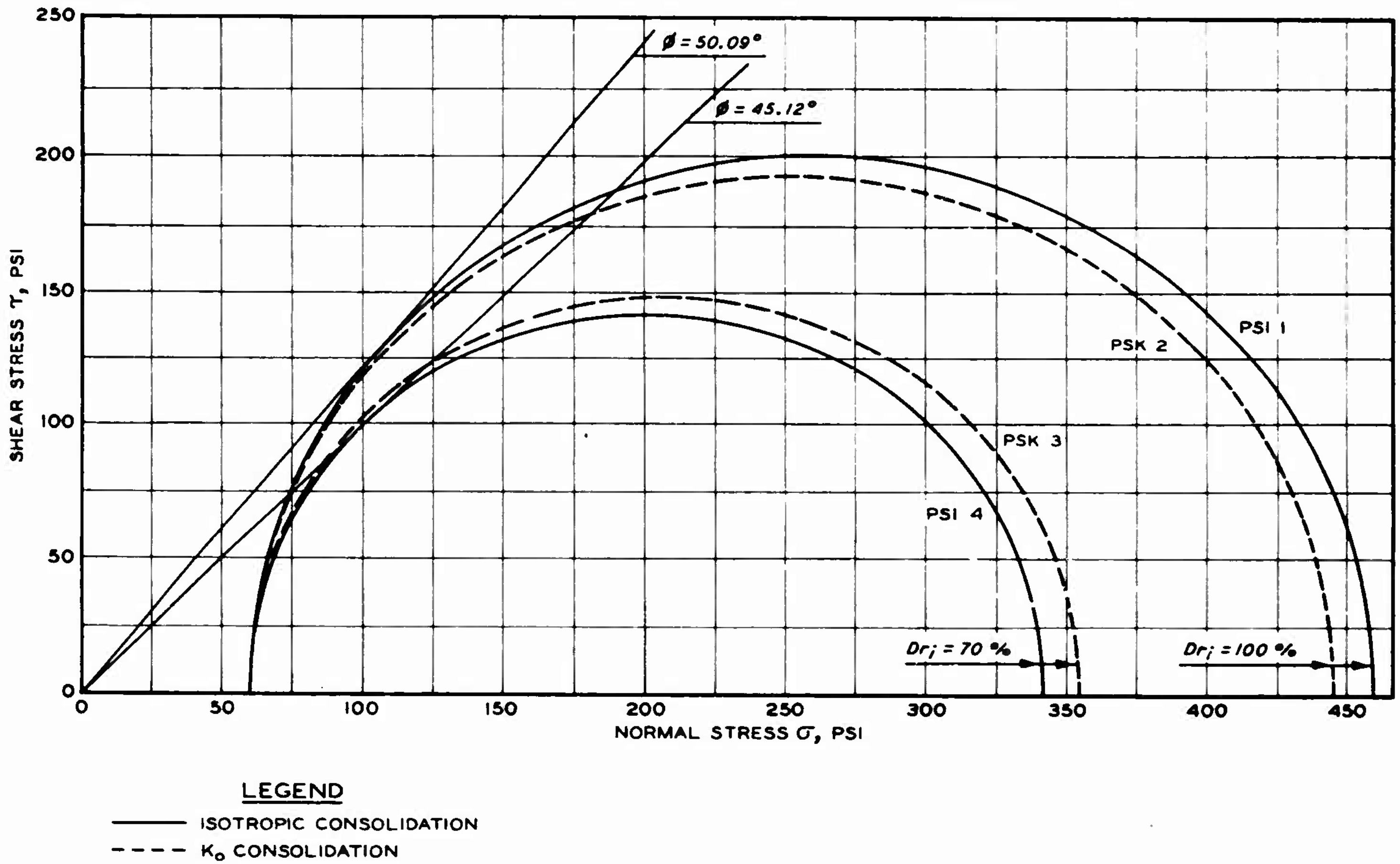


Fig. 25. Mohr's representation for the failure points

The octahedral stresses can be expressed in terms of principal effective stresses as follows:

$$\sigma_{oct} = 1/3\ (\sigma_1' + \sigma_2' + \sigma_3') \tag{3}$$

$$\tau_{oct} = 1/3 \left[(\sigma_1' - \sigma_2')^2 + (\sigma_2' - \sigma_3')^2 + (\sigma_3' - \sigma_1')^2 \right]^{\frac{1}{2}} \tag{4}$$

Thus the state of stress is reduced from three variables to two variables; also, the effect of the intermediate principal stress is included in the same manner as that of σ_1' or σ_3'. Figure 26 shows the relationship between τ_{oct} and σ'_{oct} during the entire shear stage of each of the four plane strain tests. The curve shows almost linear relationship between τ_{oct} and σ'_{oct}, and the ratio between them is not influenced by either the initial density or method of consolidation.

Intermediate principal stress

72. During consolidation the value of the intermediate principal effective stress σ_2' is equal to the value of the minor principal effective stress σ_3'. Thus if the shape of the specimen is not significant, it can be expected that there will be no difference between the behavior of plane strain and triaxial specimens during the consolidation phase of the test. Under K_o condition, the relationship between the principal stresses can be expressed as:

$$\sigma_2' = \sigma_3' = K_o\ \sigma_1' \tag{5}$$

During compression shear the value of σ_2' remains equal to σ_3' for triaxial tests, while it deviates from both σ_1' and σ_3' for plane strain tests. The relation between the three principal effective stresses during shear for plane strain tests can be the following inequality:

$$\sigma_1' > \sigma_2' > \sigma_3' \tag{6}$$

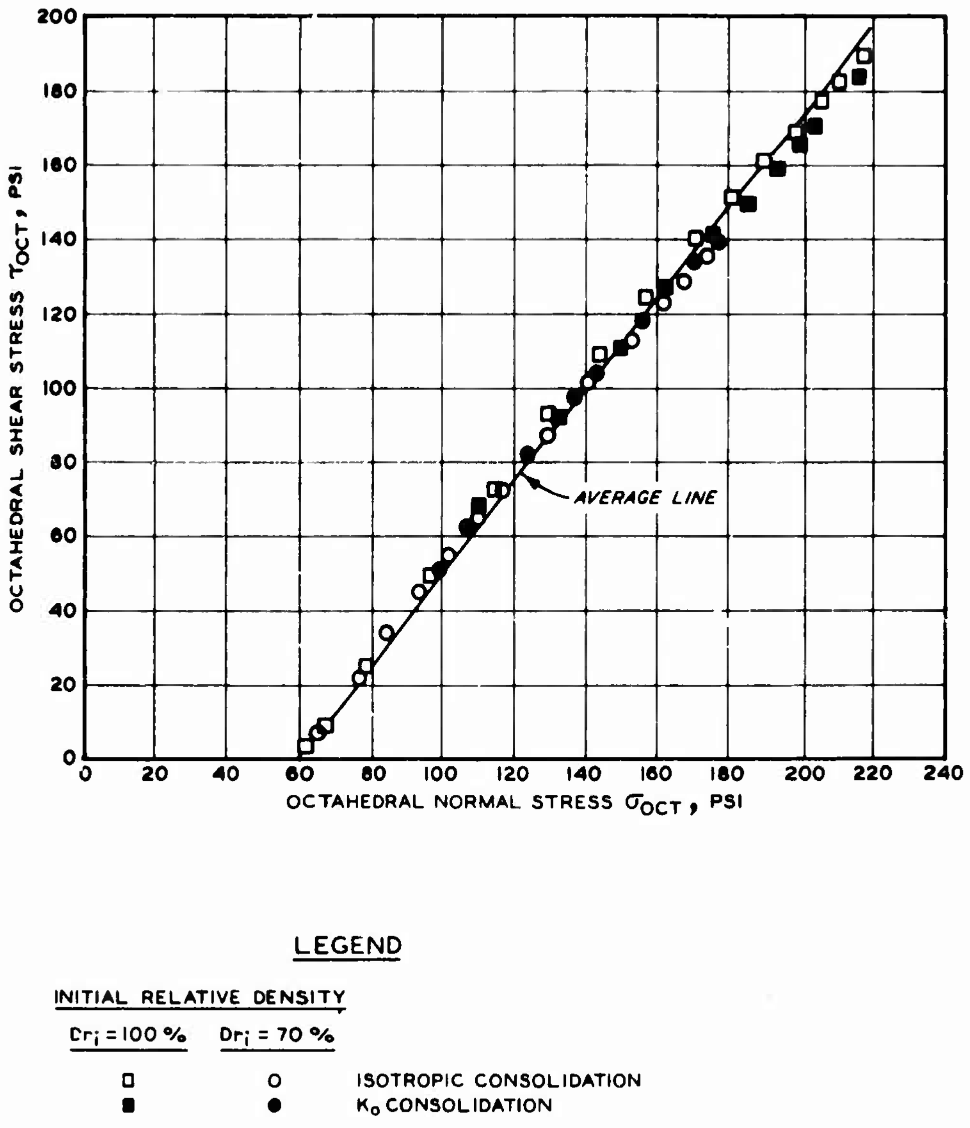


Fig. 26. Relationships between octahedral shear and octahedral normal stresses during shear

For elastic isotropic material, the value of σ_2' under plane strain condition can be expressed in terms of σ_1' and σ_2' as:

$$\sigma_2' = \nu\,(\sigma_1' + \sigma_3') \tag{7}$$

where ν = Poisson's ratio

From the above expression, the value of Poisson's ratio at any point can be expressed as

$$\nu = \frac{K_o}{1 + K_o} = \frac{\sigma_2'}{\sigma_1' + \sigma_3'} \tag{8}$$

Figure 27 shows the relationship between $\frac{\sigma_2'}{\sigma_1' + \sigma_3'}$, $\frac{\sigma_2'}{\sigma_1'}$ with respect to axial strain during shear. For isotropically consolidated specimens, the ratio $\frac{\sigma_2'}{\sigma_1'}$ started from a value of equal unity, while $\frac{\sigma_2'}{\sigma_1' + \sigma_3'}$ started from 0.5. Both ratios decrease at the beginning of shear with the increase of axial strain; then they become level up to failure, and beyond failure, they increase again. For one-dimensional consolidated specimens, the ratio of $\frac{\sigma_2'}{\sigma_1'}$ started from value equal to K_o, and $\frac{\sigma_2'}{\sigma_1' + \sigma_3'}$ started from a value equal to ν; both ratios stayed almost constant until failure, then beyond failure they increased. This observation was first noticed by Wood,[11] which led him to conclude that $\frac{\sigma_2'}{\sigma_1'}$ at failure is equal to K_o.

73. From the above discussion, it may be concluded that the value of σ_2' under plane strain condition can be expressed as

$$\frac{1}{2}\,(\sigma_1' + \sigma_3') > \sigma_2' > \nu\,(\sigma_1' + \sigma_3') \tag{9}$$

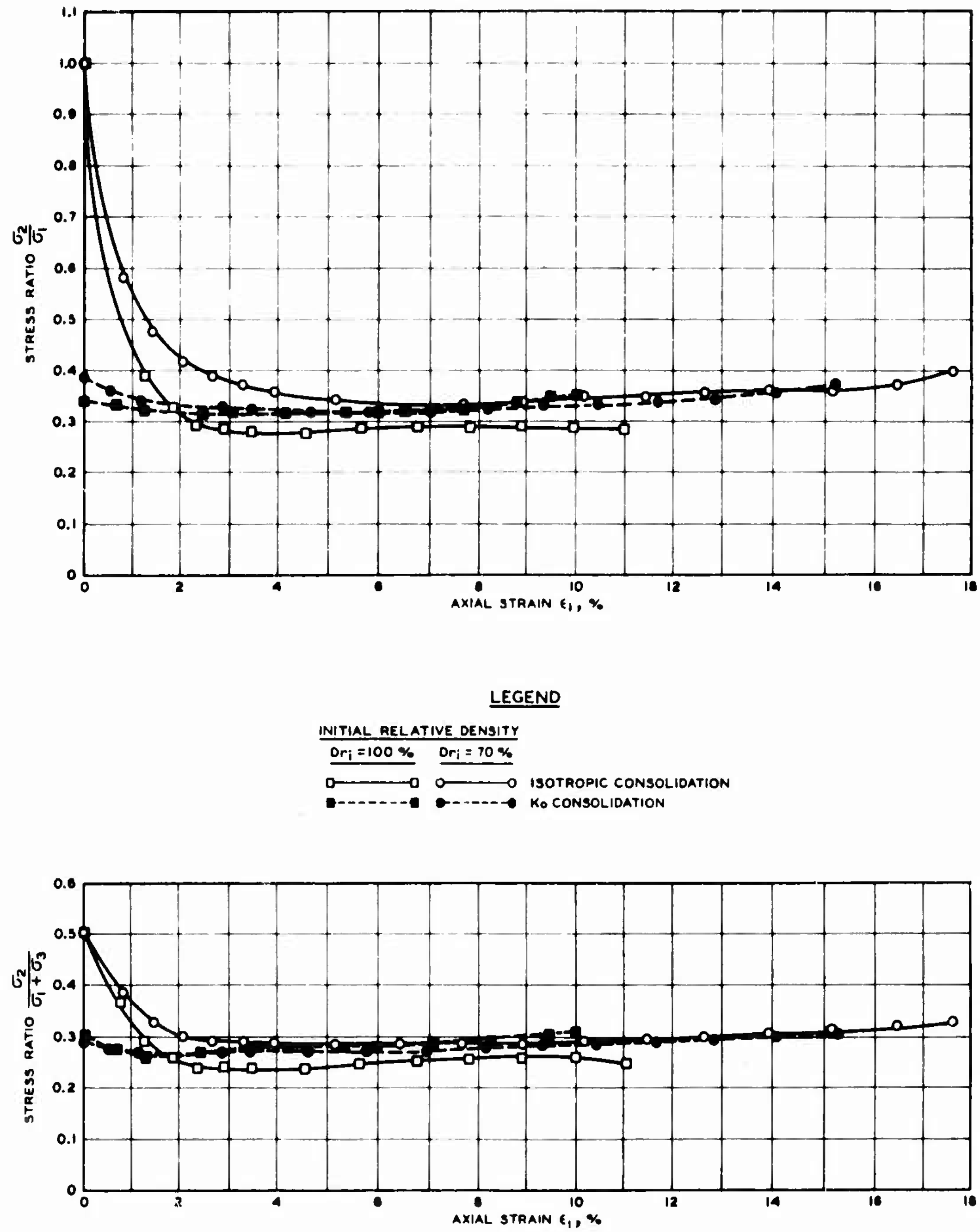


Fig. 27. Relationships between $\frac{\sigma_2'}{\sigma_1'}$, $\frac{\sigma_2'}{\sigma_1' + \sigma_3'}$ and the axial strain

PART VI: CONCLUSIONS

74. **The ~~two main~~ objectives of this investigation ~~can be stated~~ as:**

- **a. To build an apparatus that will enable soil testing under plane strain conditions.**
- **b. To demonstrate the performance of the new plane strain apparatus in testing crushed Napa basalt.**

75. The first objective was met by building a new plane strain apparatus to test cohesionless soils under plane strain condition at a wide range of densities and confining pressures. The apparatus made possible the application of three known orthogonal stresses that can be applied to a prismatic specimen and also the measurement or the control of the strains in the direction of those stresses. It is versatile enough to allow the investigator to consolidate the specimen under K_o or isotropic consolidation and shear it under either drained or undrained condition.

76. **The second objective was satisfied by conducting four different plane strain tests on crushed basalt prepared at 70 and 100 percent initial relative densities, with two specimens consolidated isotropically and the other two consolidated under K_o conditions. The new apparatus was found to be simple, precise, and efficient in operation. The results of these demonstration tests show the type of data produced by a plane strain test, the manner of reducing the data, and the graphical presentations to be made.**

77. **It is believed that the development of the WES high-capacity plane strain apparatus represents a significant addition to the capability** of the U. S. Army Corps of Engineers for investigating the physical properties of soils under conditions more closely simulating in situ conditions. This capability will be utilized for experimental work to be conducted under ES 538 and presented in subsequent reports.

LITERATURE CITED

1. Kjellman, W., "Report on an Apparatus for Consummate Investigation of the Mechanical Properties of Soil," Proceedings, First International Conference on Soil Mechanics and Foundation Engineering, Vol II, 1936, pp 16-20.

2. Lorenz, H., Neumeure, H., and Gudehus, G., "Test Concerning Compaction and Displacements Performed on Samples of Sands in the State of Plane Deformation," Proceedings, Sixth International Conference on Soil Mechanics and Foundation Engineering, Vol I, 1965, pp 293-297.

3. Bjerrum, L. and Kummencje, O., "Shearing Resistance of Sand Samples of Circular and Rectangular Cross Section," Bulletin No. 44, 1961, Norwegian Geotechnical Institute.

4. Christensen, N. H., "Model Test of Plane Active Earth Pressure in Sand," Bulletin No. 10, 1961, The Danish Geotechnical Institute.

5. Leussink, H. and Wittke, W., "Difference in Triaxial and Plane Strain Shear Strength," ASTM Special Technical Publication No. 361, 1963, pp 77-89.

6. Marsal, R. J., "Discussion on Shear Strength and Consolidation," Proceedings, Sixth International Conference on Soil Mechanics and Foundation Engineering, Vol III, 1965, pp 310-312.

7. Marsal, R. J. et al., "Research on the Behavior of Granular Material and Rockfill Samples," February 1965, Comisión Federal de Electricidad, Mexico, D.F.

8. Marsal, R. J., DeArellano, L. R., and Nunez, G. A., "Plane Strain Testing of Rockfill Materials," Proceedings of the Third Pan-American Conference on Soil Mechanics and Foundation Engineering, Vol 1, 1967, pp 249-270.

9. Smith, I. M., "An Investigation of the Strength Characteristics of Soft Clay Under Condition of Plane Strain," Graduate Research Report, 1963, University of California, Berkeley, Calif.

10. Duncan, J. M. and Seed, H. B., "Strength Variation Along Failure Surface in Clay," Proceedings, ASCE, Vol 92, No. SM6, 1966, pp 81-104.

11. Wood, C. C., "Shear Strength and Volume Change Characteristics of Compacted Soil Under Conditions of Plane Strain," PhD Thesis, 1958, University of London, London, England.

12. Cornforth, D. H., "Some Experiments on the Influence of Strain Conditions on the Strength of Sand," Geotechnique, Vol XIV, No. 2, 1964, pp 143-167.

13. Wade, N. H., "Plane Strain Failure Characteristics of Saturated Clay," PhD Thesis, 1963, University of London, London, England.

14. Dickey, J. W., Ladd, C. C., and Rixner, J. J., "A Plane Strain Shear Device for Testing Clays," Research in Earth Physics Phase Report No. 10, Contract Report No. 3-101, January 1968; prepared by Massachusetts Institute of Technology under Contract No. DA-22-079-eng-457, for U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

15. Chan, Clarence K., "University of California - Rockfill Testing Facility," paper for presentation at the Speciality Session on Mechanical Properties of Rockfill and Gravel Materials, Proceedings, Seventh International Conference on Soil Mechanics and Foundation Engineering, 1969.

16. Whitman, R. V. and Luscher, V., "Basic Experiments into Soil Structure Interaction," Journal of Soil Mechanics and Foundations Division, ASCE, Vol 88, No. SM6, 1962, pp 135-167.

17. Al-Hussaini, M. M., "The Behavior of Sand Under Plane Strain Conditions," PhD Thesis, 1968, Georgia Institute of Technology, Atlanta, Ga.

18. __________, "The Influence of End Restraint and Method of Consolidation on the Drained Triaxial Compressive Strength of Crushed Napa Basalt," Miscellaneous Paper S-70-18, June 1970, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

19. U. S. Army Engineer Division Laboratory, South Pacific, "Report of Shear Test on Crushed Rock," 1967, U. S. Army Corps of Engineers, Sausalito, California.

APPENDIX A: EVALUATION OF THE COEFFICIENT OF FRICTION

1. One major disadvantage of surrounding the soil specimen with solid plates is that friction forces may develop at the points of contact during the test. In most triaxial testing, these friction forces make the calculated soil strength higher than the actual strength. Unless proper correction is made to account for friction at the boundaries of the soil specimen, the test results might be in error.

2. Prior to the construction of the plane strain apparatus, a preliminary test was performed to evaluate the coefficient of friction between a polished stainless steel plate and a rubber membrane coated with silicone grease. The main objective of the test was to estimate friction forces that might develop at the ends of the plane specimen due to the application of the intermediate principal stress. Therefore the polished stainless steel plate used was identical to the movable plate of the apparatus and the rubber was similar to that used in actual test. The test was performed by fixing the stainless steel plate on a rigid platform, coating it with a thin film of grease, and covering it with the rubber membrane. The lower part of the shear box, used in the test, was removed, and the upper part was placed on the rubber membrane. The box was filled with crushed basalt mixed in the same proportion as that used in the actual test and then was covered with a rigid cap. Normal force was applied through a pressure-loaded piston at the top of the cap; the horizontal force was applied through a load cell. When the horizontal force reached its maximum value, a reading of both the normal force and the load cell was taken, and the normal pressure was increased to the next increment. The process was repeated, and several sets of readings for both normal and shear forces were recorded. When the results were plotted, as shown in fig. A-1, the points did not fall on a straight line; however, the average slope of the line was considered to be equal to the coefficient of friction between the specimen and the surrounding plates.

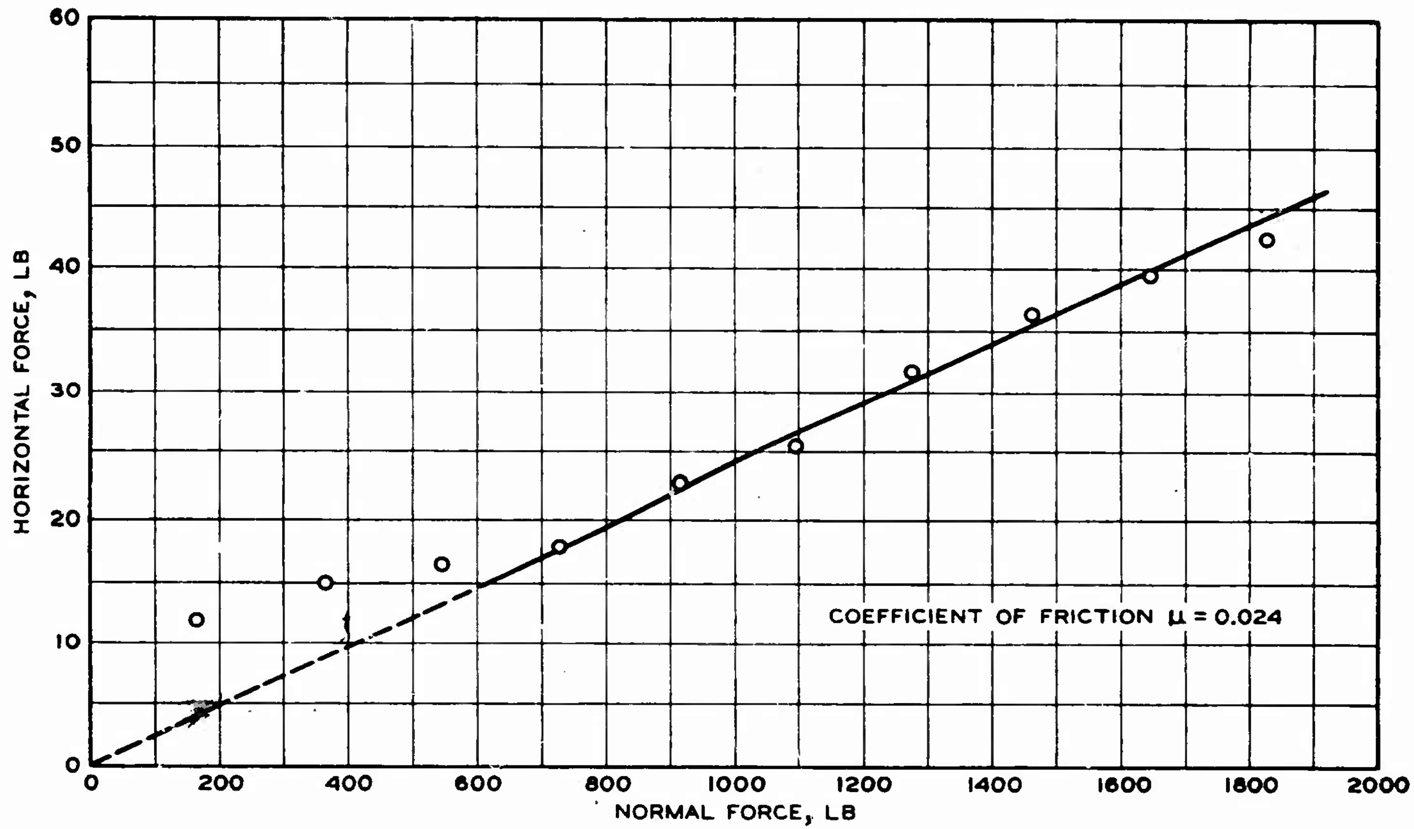


Fig. A-1. Coefficient of friction between rubber membrane and greased polished stainless steel

APPENDIX B: CORRECTION FOR THE AXIAL STRESS DUE TO END FRICTION

1. The plane strain specimen is surrounded during the test by the sliding and the movable plates that are essential to impose plane strain stress condition in the soil. Although the friction forces between these plates and the specimen are minimized by lubricated polished surfaces, the remaining friction might be significant, and test results might need to be corrected. Otherwise, part of the axial load will be used to overcome the end friction and the calculated strength of the soil will be overestimated.

2. Due to the complex nature of end friction, an exact mathematical solution is difficult to formulate; however, by introducing some simplifying assumptions, a semi-empirical solution may be obtained. These assumptions can be stated as follows: first, the intermediate principal stress σ_2 is uniformly distributed over the ends of the specimen; second, the coefficient of friction μ between the rubber membrane and the plates is constant; and third, the end friction that might develop during consolidation is neglected. Other minor assumptions may be made during the solution.

3. Consider any point A at the end of the specimen at a distance X, Y in rectangular coordinates or r, θ in polar coordinates, as shown in fig. B-1a. Assume that after the stresses were applied to the specimen, point A moved to take position B. From simple geometry, the following relationship may be obtained:

$$\frac{\Delta X}{X} = \frac{\Delta Y}{Y} = \frac{\Delta r}{r} \qquad \text{(B1)}$$

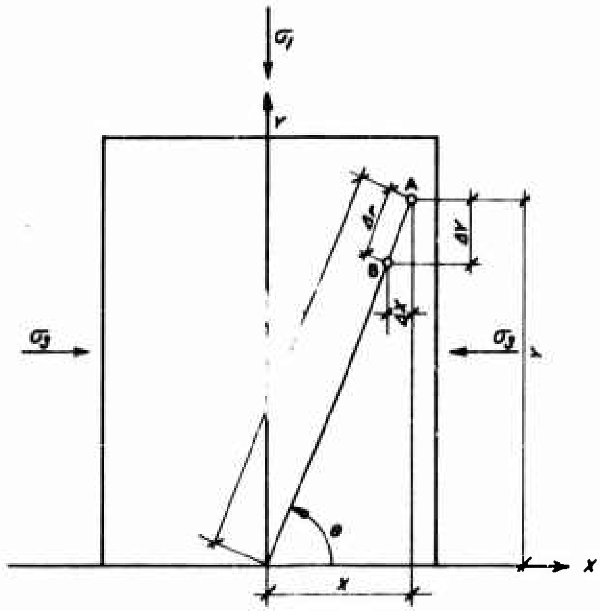
but

$$\frac{\Delta Y}{Y} = \varepsilon_1 \qquad \text{(B2)}$$

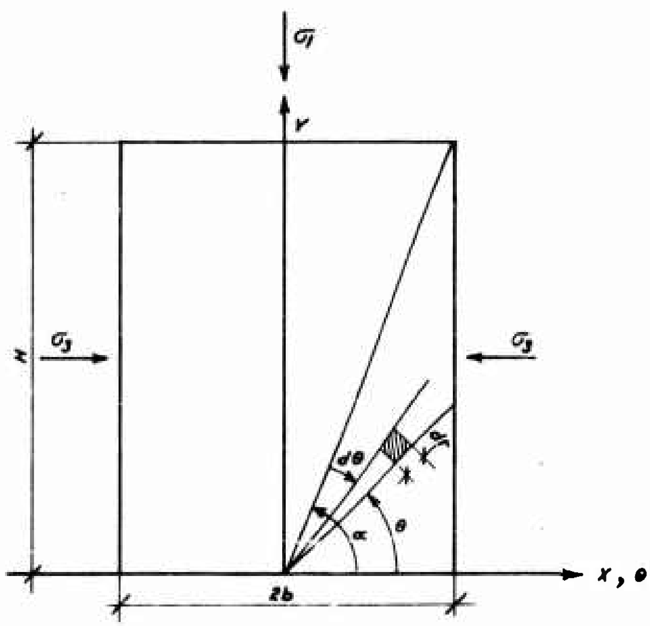
therefore

$$\Delta r = \varepsilon_1 r \qquad \text{(B3)}$$

Assume that a small element of area r dr dθ (see fig. B-1b) in the r, θ plane is acted upon by σ_2. The total friction force in the direction of motion can be expressed as $\mu \sigma_r r\, dr\, d\theta$ where μ is the coefficient of friction.



a. RECTANGULAR COORDINATE SYSTEM



b. POLAR COORDINATE SYSTEM

Fig. B-1. Representation of the area of contact between the soil specimen and the end plates in σ_2 direction

The total work done $d\,W_o$ by this element along a distance Δr is

$$d\,W_o = \mu\,\sigma_2\, r\, dr\, d\theta \cdot \Delta r = \mu\,\sigma_2\, r\, dr\, d\theta \cdot \epsilon_1\, r \tag{B4}$$

or

$$W_o = \mu\,\sigma_2 \iint \epsilon_1\, r^2 dr\, d\theta$$

The double integral can be evaluated easily around the rectangular arc with a height equal to h and a width equal to 2b . The solution of the above expression after rearranging the common term can be expressed as

$$W_o = \mu\,\sigma_2\,\epsilon_1 \left\{ \frac{b^3}{6} \left[\frac{\sin\alpha}{\cos^2\alpha} - \ln\tan\left(\frac{\alpha}{2} + \frac{\pi}{4}\right) \right] + \frac{h^3}{6} \left(\frac{\cos\alpha}{\sin^2\alpha} - \ln\tan\frac{\alpha}{2} \right) \right\} \tag{B5}$$

Substituting the numerical values of $b = 1$ and $h = 4$ and $\alpha = \tan^{1}\frac{h}{b}$, the expression can be reduced to $W_o = 7.77\,\mu\,\sigma_2\,\epsilon_1$, and the total work on both ends can be expressed as

$$W_o = 4 \times 7.77\,\mu\,\sigma_2\,\epsilon_1 = 31.08\,\mu\,\sigma_2\,\epsilon_1 \tag{B6}$$

The total input work to overcome the work done by friction is

$$W_i = L \cdot 2b \cdot (\sigma_1 - \sigma_3)\, E_1 \cdot h \tag{B7}$$

where L is the length of the specimen and $(\sigma_1 - \sigma_3)$ is the extra stress needed to overcome friction. By substituting the numerical values for L, b, and h

$$W_i = 128\,(\sigma_1 - \sigma_3)\,\epsilon_1 \tag{B8}$$

Since the input work is equal to the work done by end friction

$$128\,(\sigma_1 - \sigma_3)\,\epsilon_1 = 31.08\,\mu\,\sigma_2\,\epsilon_1$$

or

$$(\sigma_1 - \sigma_3) = 0.243\,\mu\,\sigma_2 \tag{B9}$$

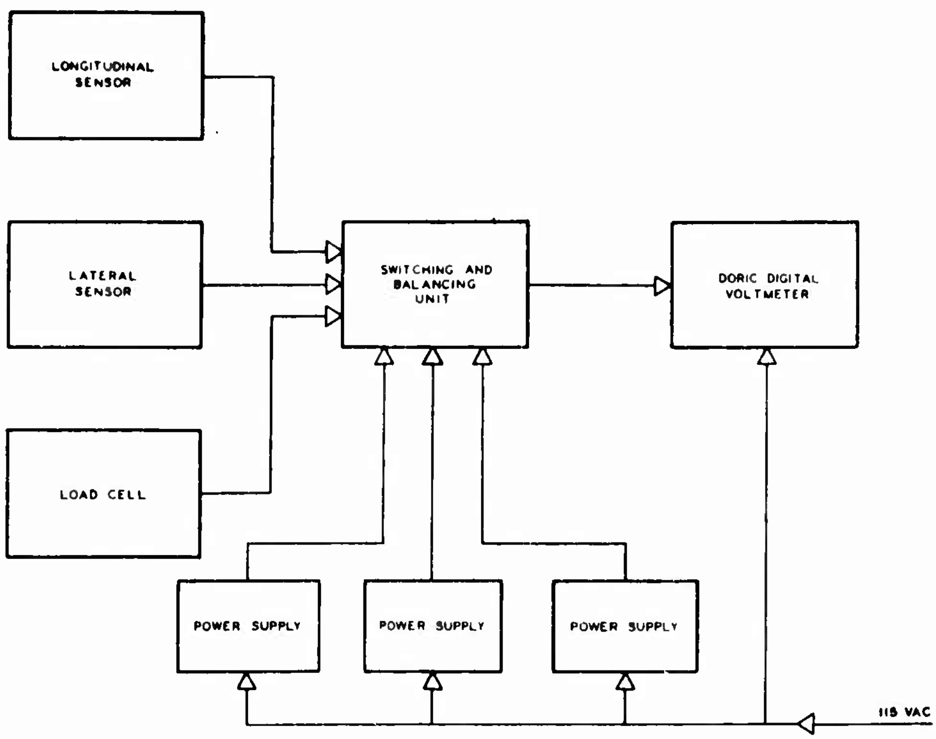
but $\mu = 0.024$ (see Appendix A); thus the correction is $(\sigma_1 - \sigma_3) = 0.005832\,\sigma_2$ or about 0.6 percent σ_2 . The above expression is derived for undrained tests and will be used for drained tests too.

APPENDIX C: CALIBRATION OF STRAIN SENSORS

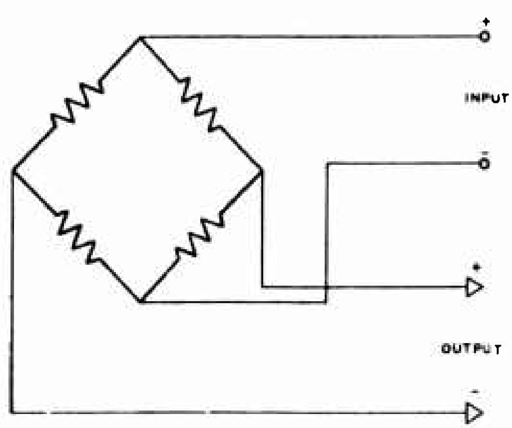
1. Calibrations of the longitudinal and lateral strain sensors were made after the strain gages were properly placed in position and connected to each other to form a temperature-compensating wheatstone bridge. The bridge was connected to a BLH Switching and Balancing Unit Model 225. The bridge was excited by a Hewlett-Packard Model 6218A, which is a DC-regulated power supply. The bridge output was displayed on a Doric Integrating Digital Microvoltmeter Model DS-100. The wiring and block diagram of the strain sensors and the electronic measuring units are shown in fig. C-1.

2. The calibration procedure used was to secure one end of the sensor in a fixed position while the displacement of the free end was measured by a Starrett precision caliper accurate to the nearest 0.001 in. Dead weights were then applied incrementally to the free end, and measurements of the output voltage and the deflection of the free end were recorded after each load increment. Calibration curves for the two sensors are given in fig. C-2.

3. The sensitivity of the strain sensors with respect to the cell pressure was also checked. This was accomplished by placing the longitudinal and lateral sensors inside the pressure chamber and recording measurements of the output voltage with respect to the increase in cell pressure. The relationship between the change in the output voltage and the cell pressure is shown in fig. C-3.



a. BLOCK DIAGRAM OF PLANE STRAIN ELECTRONIC MEASURING SYSTEM



b. SENSOR WIRING DIAGRAM

Fig. C-1. Wiring and block diagrams of strain sensors and electronic measuring units

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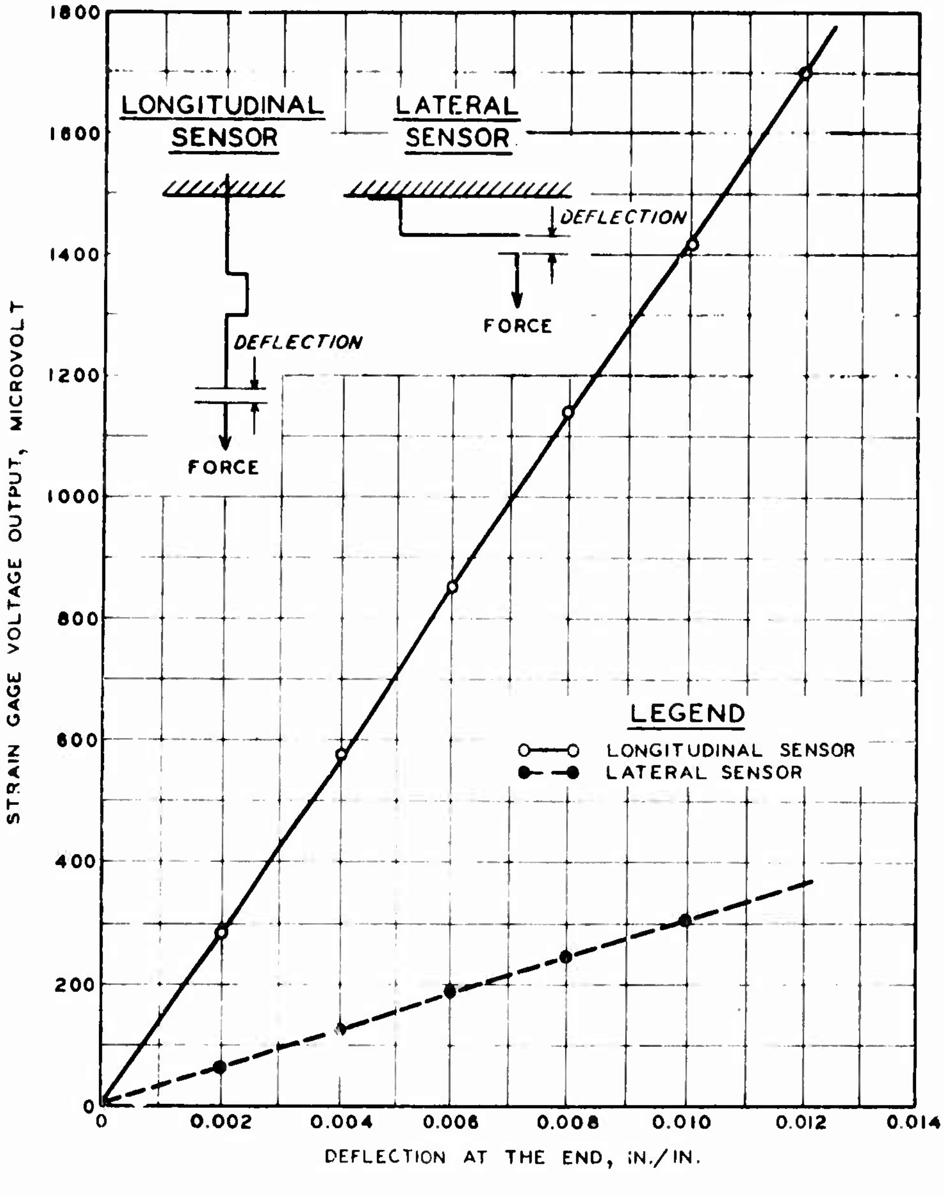

Fig. C-2. Correlation curves of output voltage versus end deflection of longitudinal and lateral strain sensors

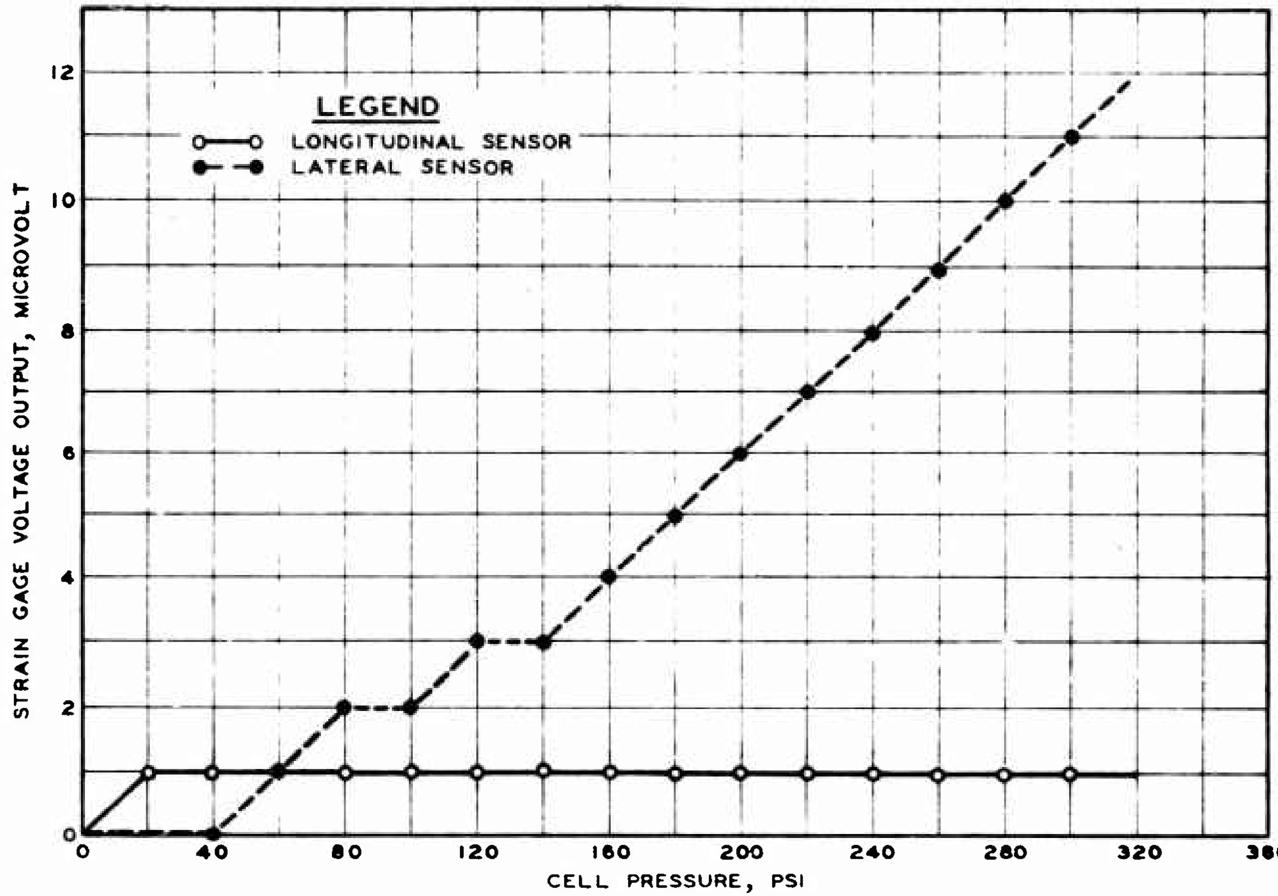

Fig. C-3. Correlation curves of output voltage versus cell pressure for longitudinal and lateral strain sensors

APPENDIX D: PREPARATION OF RUBBER MEMBRANE

1. Since there is no commercially available rubber membrane that can be used in plane strain testing, it was decided to produce a rubber membrane for a prismatic specimen at the laboratory. The material was rubber latex Brand IVII, which was obtained from General Latex and Chemical Corporation of Ohio. A prismatic aluminum mold (see fig. D-1), 16-1/8 in. long, 2 in. wide, and 6-3/4 in. high, was made for making the membrane. The liquid latex was placed inside a rectangular plastic box to be used as a bath for the aluminum mold.

2. The procedure for making the rubber membrane consisted of dipping the mold slowly into the liquid latex bath until the mold was completely covered; then the mold was slowly withdrawn from the liquid. The process of dipping and removing the mold took about two minutes. After that, the mold was left for a minimum of three hours in the air to dry. In the second dip, the mold was inverted in such a manner that the top of the mold was immersed first in the liquid latex in order to obtain a more uniform thickness throughout the membrane. It was found that each dip corresponded to a membrane of about 0.004 in. thick. After the mold had been dipped fourteen times in the liquid latex, it was allowed to dry in air for a period of two days.

3. When the air drying of the rubber latex was over, the upper and lower surfaces of the rubber were cut away to fit the platens of the plane strain apparatus. After being trimmed, the rubber membrane was allowed to cure in an oven at 125 F for a period of two hours. Finally, the membrane was stripped from the aluminum mold, dusted with talcum powder and stored for future use.

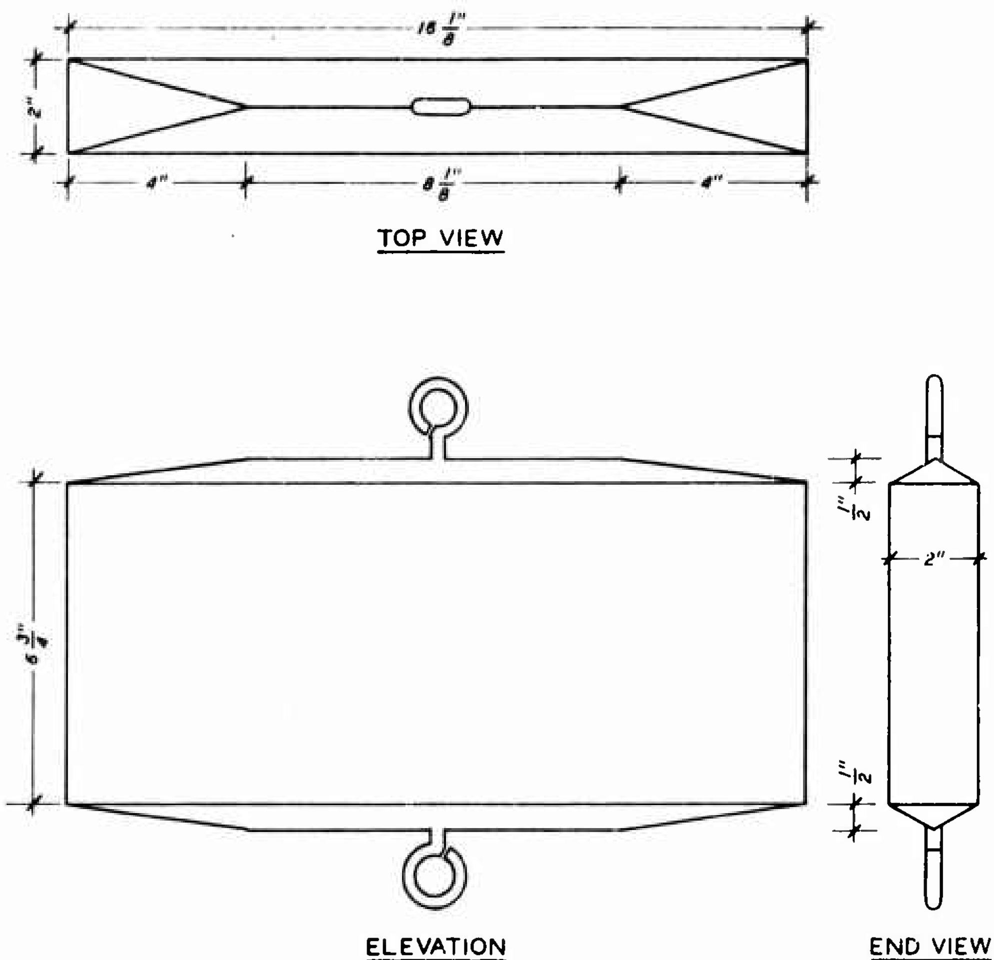

Fig. D-1. Aluminum mold for the rubber membrane

APPENDIX E: COMPUTER PROGRAM

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HUSSAINI     THE GE-400 SERIES - FORTRAN ASA (DARS)              PAGE #    1    HUSS  FH2619

      C     ANALYSIS OF PLANE STRAIN TEST OF SAND DURING SHEAR
            DIMENSION  A1(50),SR1(50),SR2(50),SR3(50),F1(50),F2(50),DELTAH(50)
      C     VARIABLE  MS CHANGED TO HS
           1,U(50),S1(50),S2(50),S3(50),A2(50),E1(50),DELTAV(50),PPPA(50),
           2OCTSR(90),VRDG(90),HS(90),OCTS(90),OCSRAN(90),VSTRAN(90)
           3,HRDG(50),BP(50),X(50),DELTAU(50),E2(50),E3(50),E(50),CELLPR(50),
           4S1MS3(90),S2S1R(90),S3S1R(90),F3(90)
        300 READ 1
            CALL EOFTST(50,NFILE)
            IF(NFILE.EQ.2) GO TO 99
            READ 2, YO, DO, HO, DELVO, DELHO, SR10, SR20, SR30
            READ 10,N
            READ 4, (SR1(I),SR2(I),SR3(I),HRDG(I),VRDG(I),CELLPR(I),BP(I),I=1,
           1N)
            VO=YO*HO*DO
            Q=1.0E-11
            PRINT 3
            PRINT 11
            PRINT 1
            PRINT 11
            PRINT 9
            PRINT 11
            PRINT 5
            PRINT 11
            DO 50 I=1,N
            F1(I)=1.000*(SR1(I)-SR10)
            F2(I)=0.50000*(SR2(I)-SR20)
            F3(I) = F1(I) - 3.1416*CELLPR(I)
            U(I)=1.00000  *(SR3(I)-SR30)+BP(I)
            IF (I-1) 55,56,55
         56 UO=U(I)
         55 DELTAU(I)= U(I)-U)
            DELTAH(I)=DELHO-HRDG(I)
            E1(I)=DELTAH(I)/HO
            DELTAV(I)=(VRDG(I)-DELVO)/16.39
            VSTRAN(I)=DELTAV(I)/VO
            E3(I)=-(VSTRAN(I)+E1(I))
            A1(I)=YO*DO*(1.+DELTAV(I)/VO)/(1.-E1(I))
            A2(I)=HO*DO*(1.+DELTAV(I)/VO)
            S3(I)=CELLPR(I)-U(I)
            S2(I)=F2(I)/A2(I)+S3(I)
            S1(I)=F3(I)/A1(I)+S3(I)
            S1MS3(I)=S1(I)-S3(I)
            IF (I-1) 60,61,60
         61 S1MS30 =S1MS3(I)
         60 X(I)=S1MS3(I)-S1MS30
            QA =ABS(X(I))
            IF (QA-Q) 71,71,72
         71 PPPA(I)=1.0E51
            GO TO 73
         72 PPPA(I)=DELTAU(I)/X(I)
         73 S2S1R(I)=S2(I)/S1(I)
            S3S1R(I)=S3(I)/S1(I)
            OCSRAN(I)=2./3.*SQRT(E1(I)**2+E3(I)**2+(E1(I)-E3(I))**2)
            HS(I)=  (S1(I)+S2(I)+S3(I))/3.
            OCTS(I)=1./3.*SQRT((S1(I)-S2(I))**2 + (S2(I)-S3(I))**2
           1  + (S3(I)-S1(I))**2 )
            OCTSR(I)=OCTS(I)/HS(I)
         50 PRINT 6 , S1(I),S2(I),S3(I),S1MS3(I),E1(I),S2S1R(I),S3S1R(I),
           1HS(I),OCTS(I),CELLPR(I),U(I)
            PRINT  11
            PRINT 11
            PRINT 11
            PRINT 7
            PRINT 11
            DO 200 I=1,N
        200 PRINT 8, DELTAH(I),DELTAV(I),E1(I),VSTRAN(I),OCSRAN(I),E3(I),
           1OCTSR(I),F1(I),F2(I),PPPA(I)
            GO TO 300
          1 FORMAT (50H1                                                    )
          2 FORMAT (5F7.3,3I7)
         10 FORMAT (I5)
          3 FORMAT(1H1,3X30HSAMPLENO     TEST COMPLETED     )
         11 FORMAT (1H0)
          4 FORMAT (3I6,4F8.3)
          5 FORMAT (3X,80H S1      S2      S3  S1MINUSS3  E1     S2S1RATIO S3S1RA
           1TIO  HS     OCTS  CELLPR  U        )
          6 FORMAT (1X3F7.2,F8.2,F8.4,F8.3,F10.3,4F7.1)
          9 FORMAT (3X,11HSHEAR STAGE)
          8 FORMAT (1XF7.3,F8.3,F8.4,F9.4,F10.4,2F9.4,2I7,F8.3)
          7 FORMAT (1X, 85H DELTAH DELTAV    E1      VOLSTRAIN  OCTSTRAIN    E3
           1 OCTSRATIO  F1      F2     PPPA            )
         99 CALL EXIT
            END
```